



Research papers

A drought index: The standardized precipitation evapotranspiration runoff index

Long Wang^{a,b}, Hang Yu^{a,*}, Maoling Yang^c, Rui Yang^a, Rui Gao^a, Ying Wang^a^a College of Water Conservancy, Yunnan Agricultural University, China^b IHE Delft Institute for Water Education, Netherlands^c Survey Design Institute of Water Conservancy and Hydropower in Zhaotong, China

ARTICLE INFO

This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Antonino Cancelliere, Associate Editor

Keywords:

SPERI

SPEI

SPI

Copula function

ABSTRACT

Based on the principles underlying the calculation of the standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI), this study selects precipitation, temperature, relative humidity, sunshine hours, wind speed and runoff data to develop a multi-scalar drought index, the standardized precipitation evapotranspiration runoff index (SPERI), using methods such as Penman-Monteith and Copula. This index is applied along with the SPI and SPEI to Yunnan Province of China. The results show that the changes in the SPERI are close to those in the SPI and SPEI. They are well correlated and can all reflect drought conditions. In addition, comparisons among these three drought indexes and the actual extreme drought during September 2009–August 2010 showed that the SPERI was superior to the SPI and SPEI and that the 3-month SPERI assessment was the most accurate. Therefore, the SPERI can be used to analyze, assess and forecast drought conditions in different areas as well as to assess the impacts of climate change on drought.

1. Introduction

Droughts are among the main natural hazards leading to agricultural, economic and environmental damage (Burton et al., 1978; Wilhite and Glantz, 1985). Global economic losses due to droughts are estimated to be as high as 600–800 million dollars per year, which are much greater than those due to other meteorological disasters (Wilhite, 2000). Therefore, it is necessary to conduct drought monitoring and assessment globally or in each area in order to determine drought intensity, magnitude, duration and spatial extent and to provide a basis for fighting drought and drought relief. Therefore, it is necessary to select or develop an index to describe drought.

Because droughts in each area of the globe differ significantly, various industrial departments in each region and country have proposed numerous different drought indexes. More than 58 types of drought indexes from different countries are listed in the technical report of the World Meteorological Organization (WMO) (WMO, 1975, 2016). In addition, the Bulletin of the American Meteorological Society (BAMS) published a special issue in 2002 to discuss drought indexes (Heim, 2002; Redmond, 2002; Keyantash and Dracup, 2002; Svoboda et al., 2002; Lawrimore et al., 2002). Among the many drought indexes, the most widely used are the Palmer drought severity index (PDSI) based on the soil moisture balance equation (Palmer, 1965), the

standardized precipitation index (SPI) based on a precipitation probabilistic approach (McKee et al., 1993), and the standardized precipitation evapotranspiration index (SPEI) based on the water balance (deficit or surplus) probabilistic method (Vicente-Serrano et al., 2010a).

The PDSI is a milestone in the development of drought indexes and is based on the demand in the water balance equation to analyze the dry (negative) and wet (positive) changes in semi-arid and semi-wet areas (Heim, 2002; Vicente-Serrano et al., 2010a). Numerous scholars have by now explained the calculation process of the PDSI and its meanings (Karl, 1983, 1986; Alley, 1984). Although the PDSI is widely used, it also suffers drawbacks (Hayes, 2000; Keyantash and Dracup, 2002; Alley, 1984; Karl, 1986; Soulé, 1992; Akinremi et al., 1996; Weber and Nkemdirim, 1998; Vicente-Serrano et al., 2010a). Some of the drawbacks can be solved by developing the self-calibrated PDSI (Wells et al., 2004), but the main drawback of the PDSI remains unsolved. That drawback is related to its fixed temporal scale (9–12 months) and auto-regression characteristics, which are subject to the values of the past four years (Guttman, 1998).

The SPI is the quantile of the standard normal distribution transformed from the precipitation distribution function. Therefore, it can be used to compare dry and wet conditions in different areas. In addition, it can be used to calculate dry and wet conditions at different temporal scales (e.g., 1, 3, 6, 12, 18 and 24 months). Thus, the SPI has been

* Corresponding author at: College of Water Conservancy, Yunnan Agricultural University, China (H. Yu).

E-mail addresses: ynndwl@126.com (L. Wang), wolf5666@163.com (H. Yu).

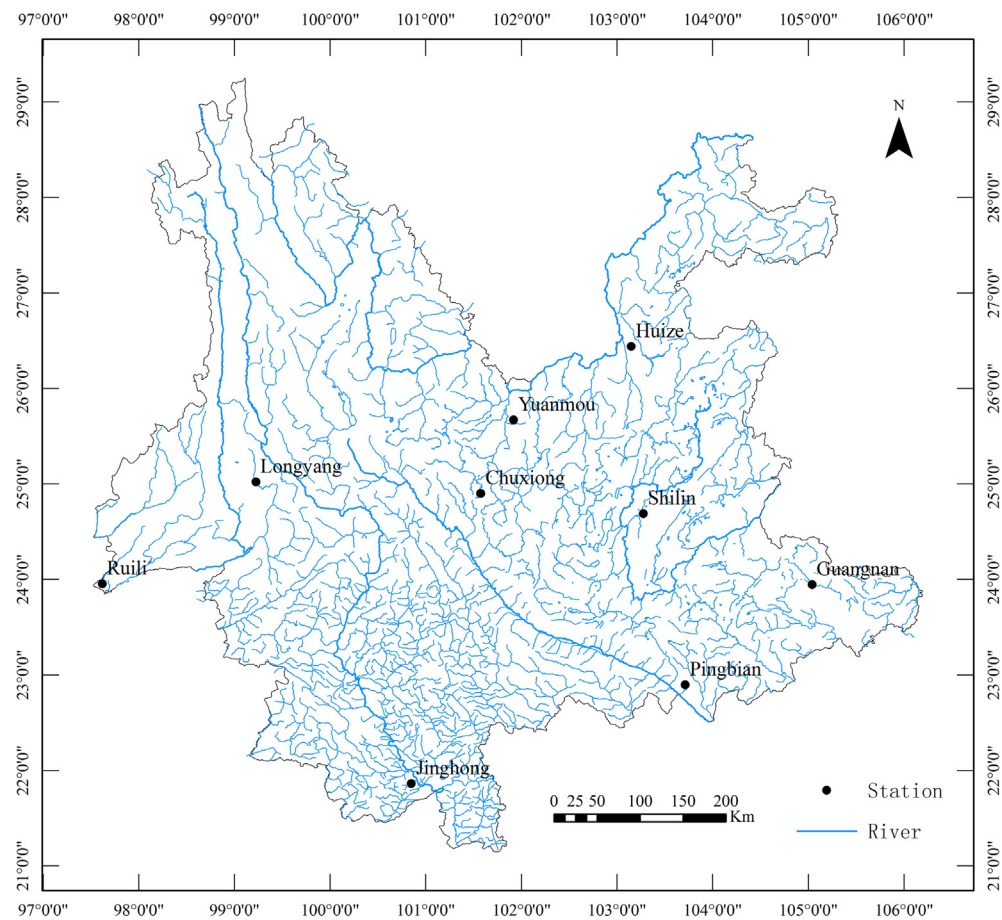


Fig. 1. Locations of the stations in Yunnan.

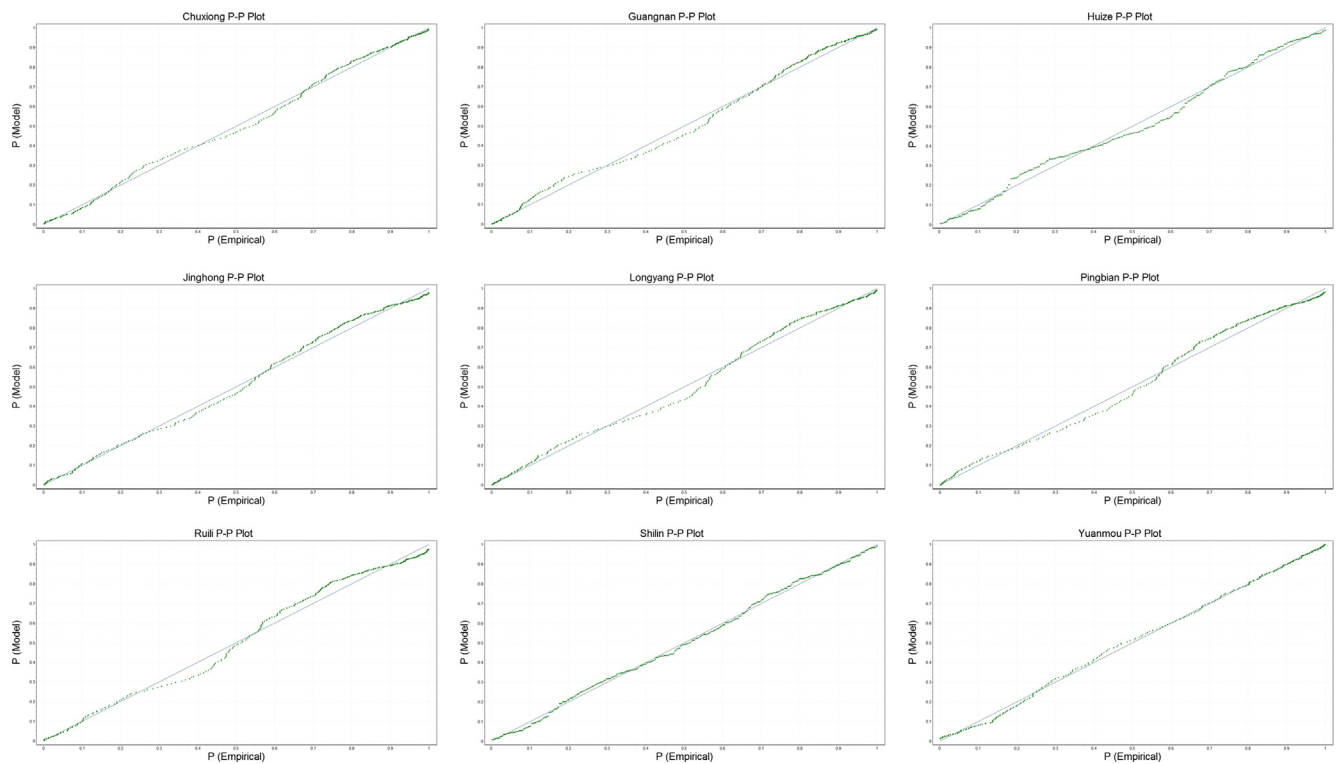


Fig. 2. P-P plot of P-PET at a temporal scale of 1 month.

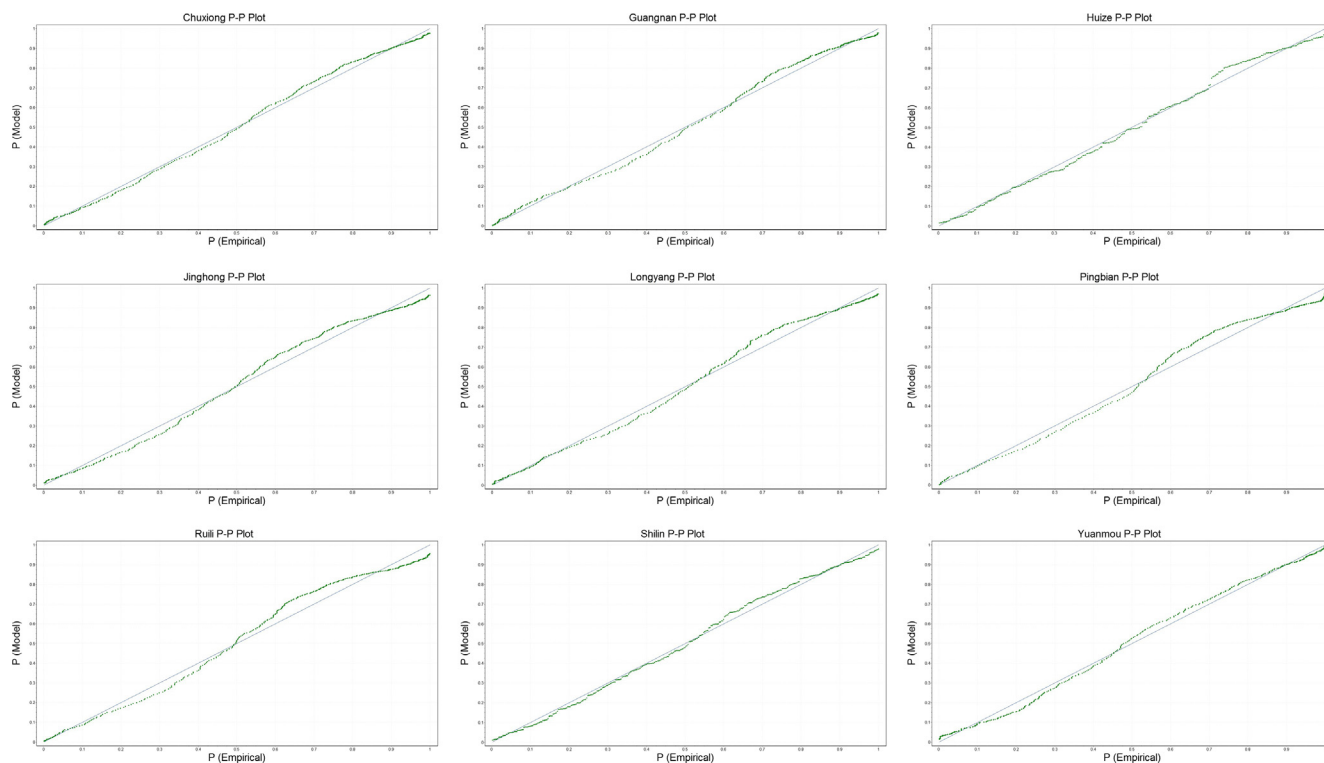


Fig. 3. P-P plot of P-PET at a temporal scale of 3 months.

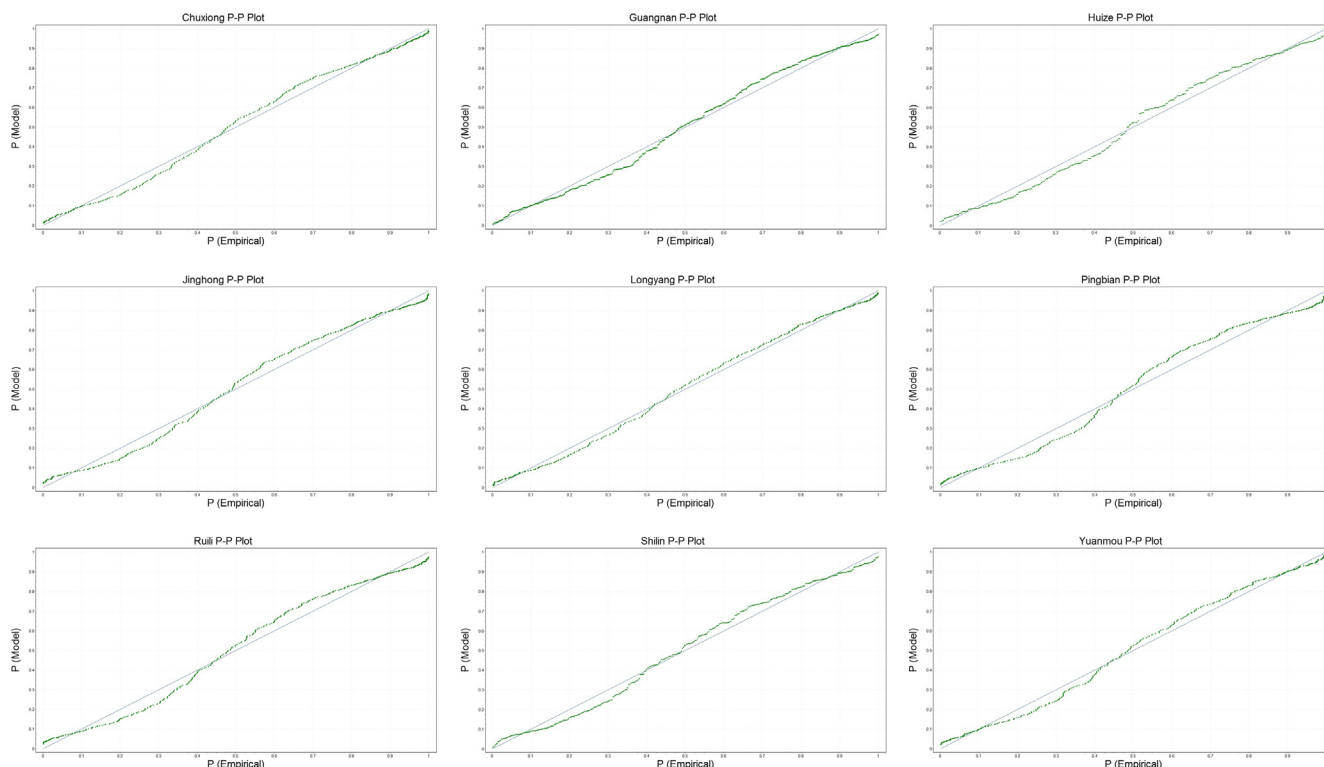


Fig. 4. P-P plot of P-PET at a temporal scale of 6 months.

widely used in dry and wet analyses in different areas. Because the SPI is calculated based on precipitation data, it does not consider other variables that affect drought (such as temperature and evapotranspiration). In addition, this index is based on two assumptions: (1) the change in precipitation is much larger than those in other variables such as temperature and potential evapotranspiration (PET), and (2)

other variables are stable and do not have temporal trends (Vicente-Serrano et al., 2010a,b,c). Therefore, SPI is mainly used in areas with great precipitation impacts.

The SPEI is based on the difference between precipitation (P) and PET (water balance) and is calculated using the SPI method. Vicente-Serrano et al. (2010a,b, 2011a,b, 2012a) provided the comprehensive

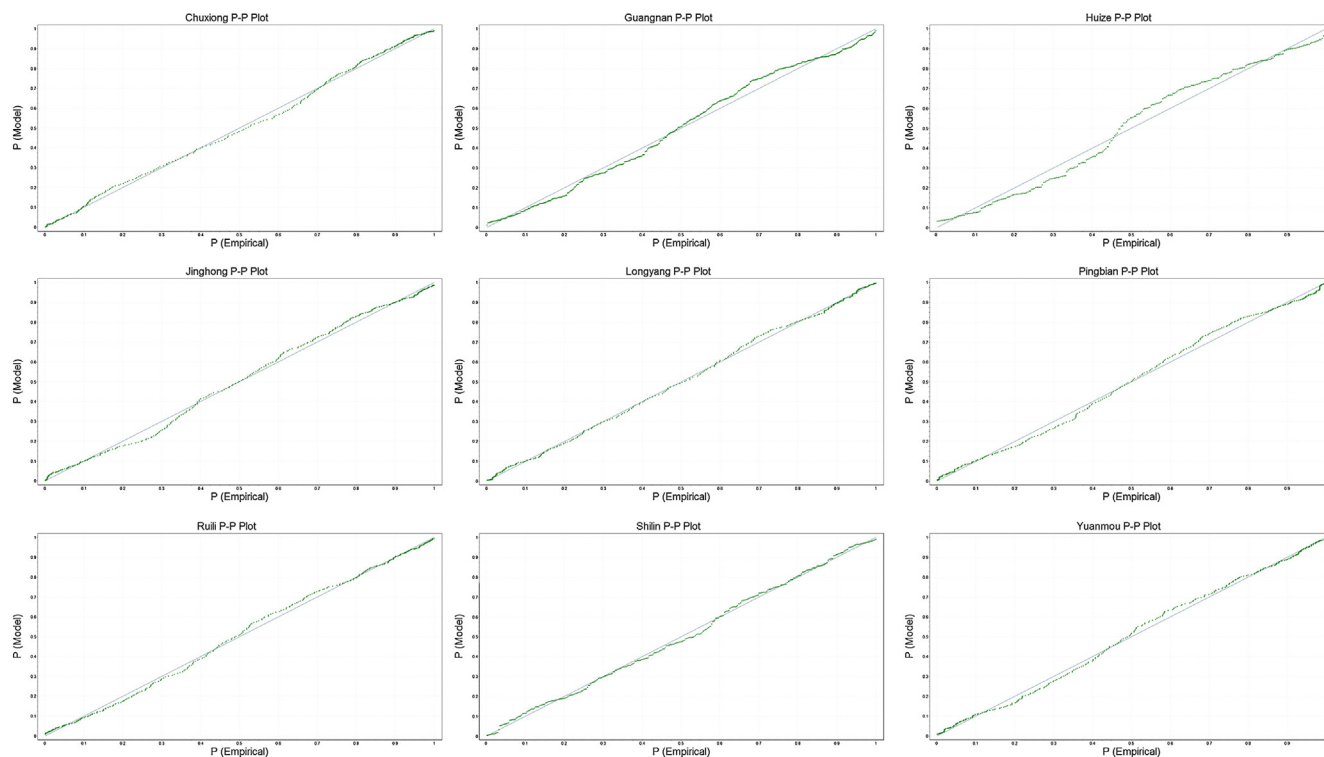


Fig. 5. P-P plot of P-PET at a temporal scale of 12 months.

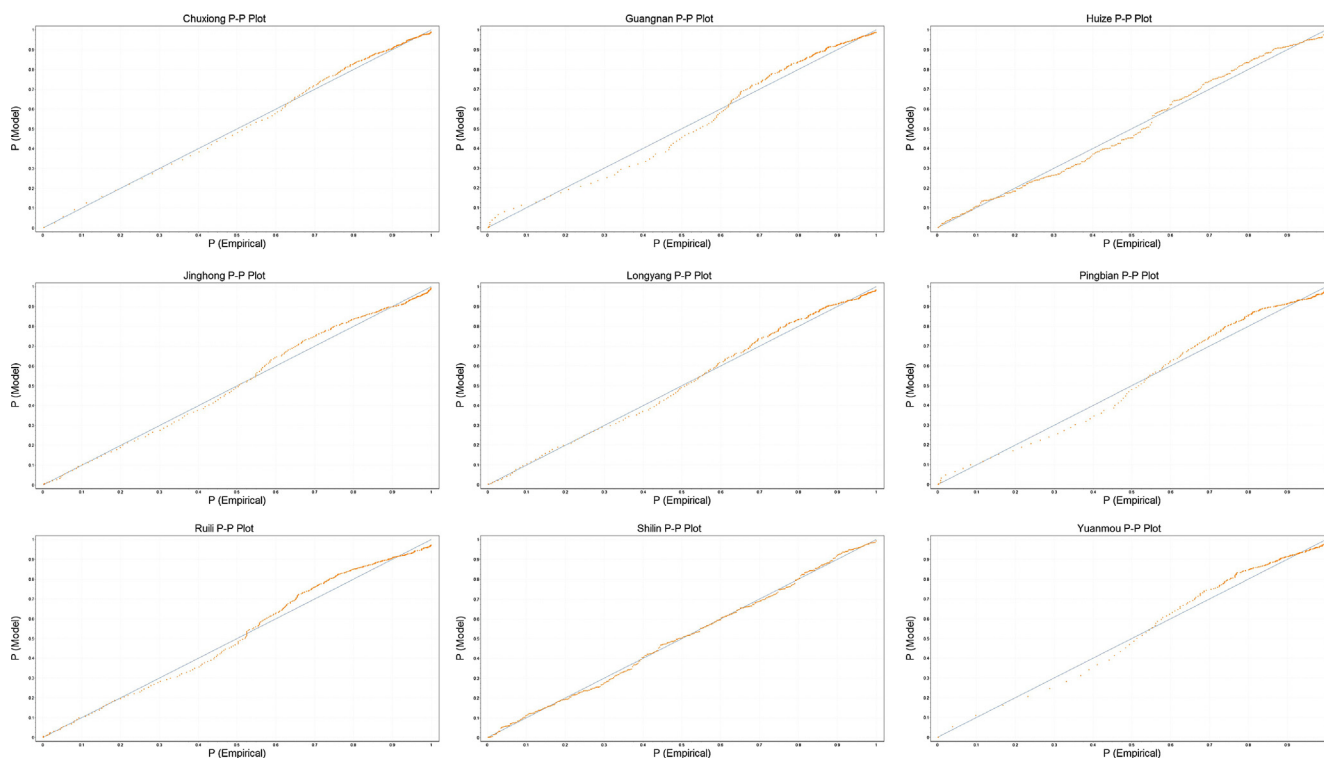


Fig. 6. P-P plot of runoff at a temporal scale of 1 month.

theory and calculation details of this index. Since proposed in 2010, the index has been widely used in different research areas (Beguería et al., 2014), including investigations of drought changes, drought reconstructions, climate changes and the impacts of drought on hydrology, agriculture and ecosystems (Potop, 2011; Li et al., 2012; Paulo et al., 2012; Sohn et al., 2013; Allen et al., 2011; Boroneant and Ionita,

2011; Wolf and Abatzoglou, 2011; Abiodun et al., 2013; Soo-Jin et al., 2013; Yu et al., 2013; Lorenzo-Lacruz et al., 2010; Potop et al., 2012; Vicente-Serrano et al., 2010c, 2011b, 2012b, 2013; Toromani and Pasho, 2011; Drew et al., 2013; Barbata et al., 2013; Cavin et al., 2013). Although the SPEI considers climatic water balance, it does not sufficiently consider the impact of runoff on drought. For multi-year

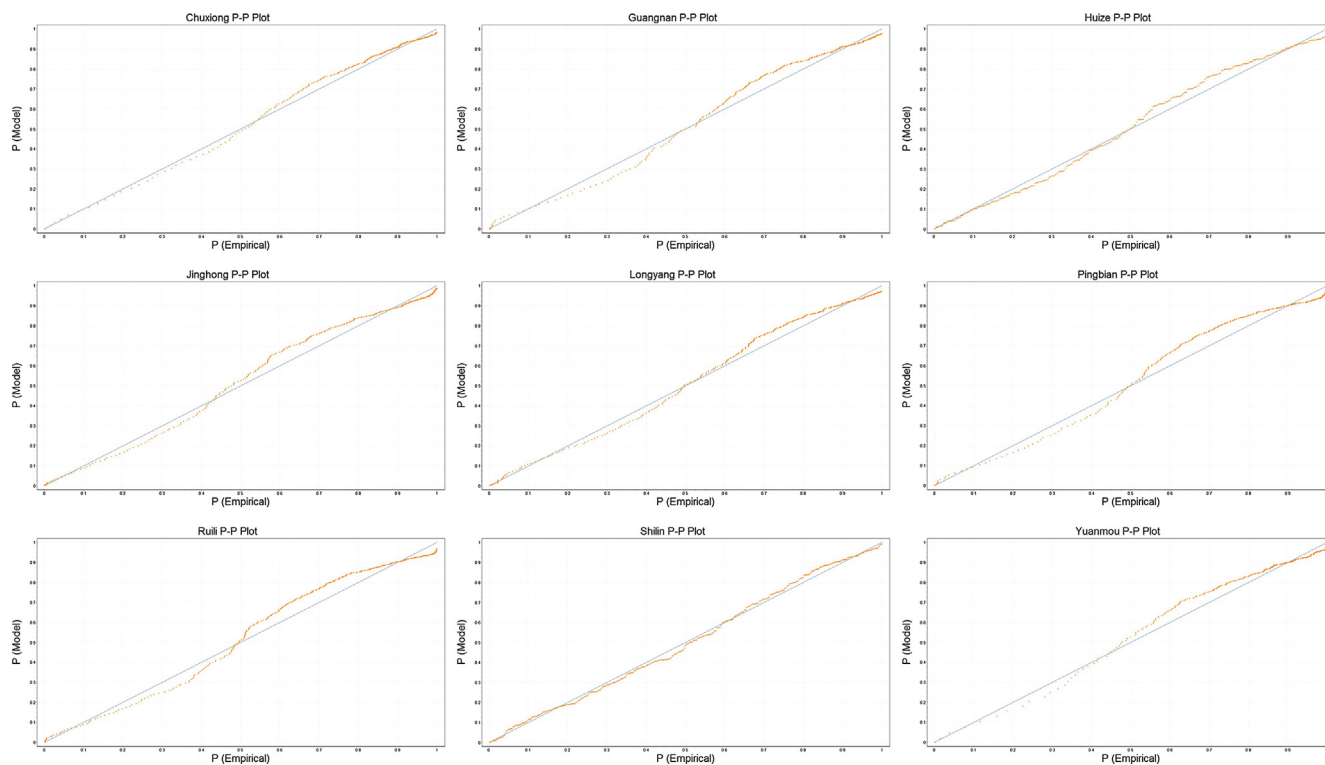


Fig. 7. P-P plot of runoff at a temporal scale of 3 months.

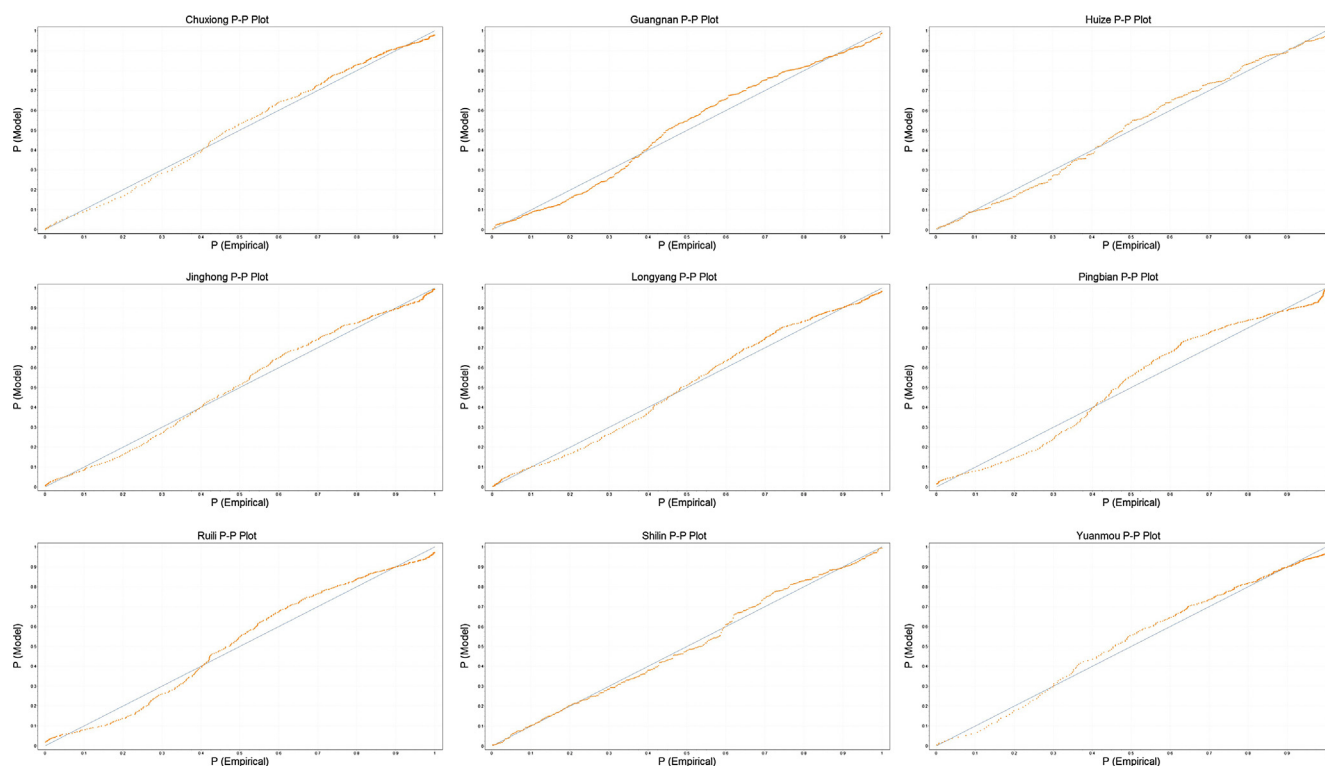


Fig. 8. P-P plot of runoff at a temporal scale of 6 months.

averages and closed watersheds, precipitation minus evapotranspiration is equal to runoff. However, for drought, people generally care about drought in a certain area (primarily unclosed watersheds) in specific periods (unmulti-year averages). Thus, it is necessary to consider the impact of runoff on drought.

Therefore, based on the advantages of the PDSI, SPI and SPEI (the

effects of precipitation and evapotranspiration on drought and multi-scalar effects), this study develops a new index that considers the runoff effect: the standardized precipitation evapotranspiration runoff index (SPERI). Based on the calculation principle of the SPI and SPEI, this index first calculates P-PET, then uses a two-dimensional Copula function to calculate the joint distribution function of P-PET and runoff,

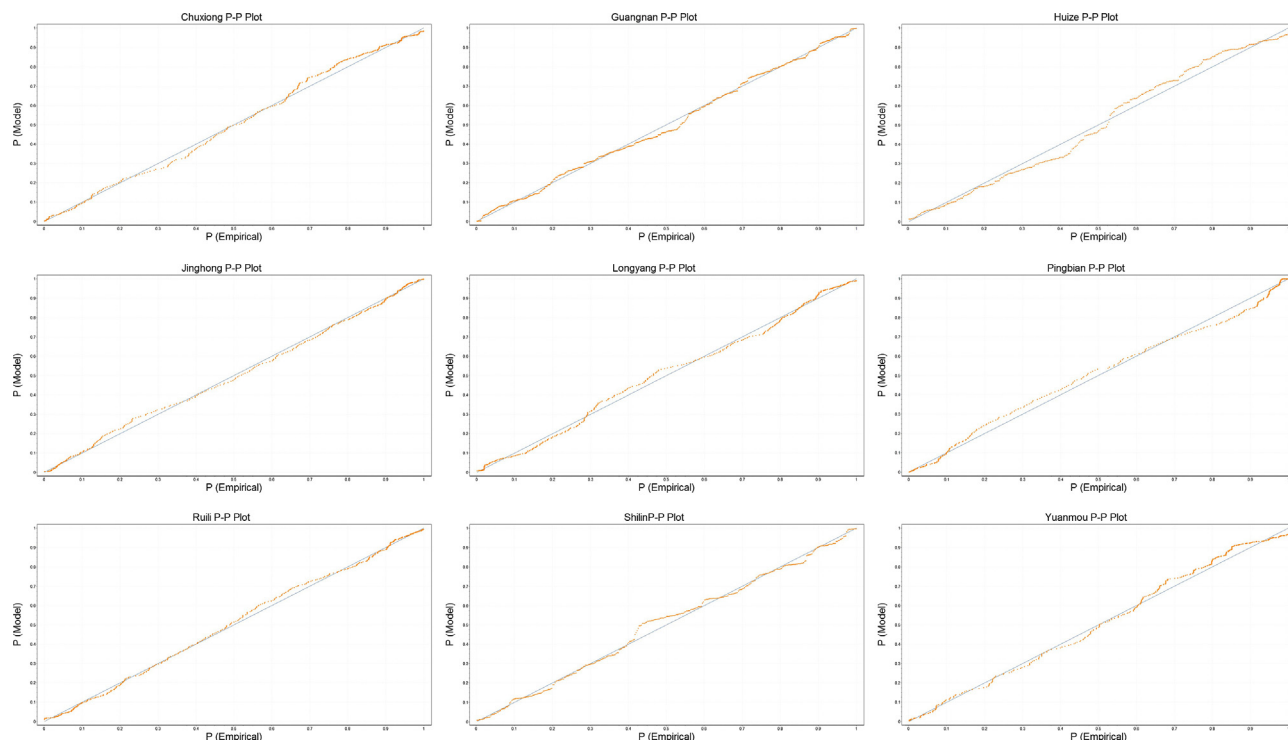


Fig. 9. P-P plot of runoff at a temporal scale of 12 months.

Table 1

P-PET (Log-Logistic distribution) and runoff (Lognormal distribution) parameters.

Distribution (time scale)	Parameter	Chuxiong	Guangan	Huize	Jinghong	Longyang	Pingbian	Ruili	Shilin	Yuanmou
Lognormal (1-month)	μ	1.390	2.820	3.676	2.568	2.515	3.656	3.200	1.421	2.008
	σ	1.397	1.122	1.105	0.867	0.988	1.129	0.972	0.938	1.680
	γ	-0.074	3.016	11.786	-1.364	0.103	13.411	0.817	-0.136	0.238
Log-Logistic (1-month)	α	4.536	4.267	5.322	3.075	4.249	2.505	2.491	4.230	15.376
	β	193.810	151.930	189.860	135.310	169.540	125.580	144.150	191.900	636.270
	γ	-231.920	-165.890	-227.030	-158.060	-197.400	-99.431	-154.520	-220.160	-712.300
Lognormal (3-month)	μ	2.669	3.988	4.850	3.710	3.745	4.867	4.363	2.647	3.333
	σ	1.252	1.077	1.030	0.783	0.846	1.033	0.867	0.817	1.540
	γ	-0.037	11.324	39.505	-2.706	-0.462	42.150	4.981	-0.748	1.231
Log-Logistic (3-month)	α	4.585	3.763	5.397	3.278	3.854	2.252	2.375	3.676	8.225
	β	493.050	316.820	467.370	364.580	365.390	297.100	356.730	421.380	0.046
	γ	-595.190	-348.550	-568.170	-410.580	-435.770	-201.130	-367.500	-498.610	-3954.800
Lognormal (6-month)	μ	3.676	5.024	5.899	4.777	4.771	6.219	5.547	3.634	4.500
	σ	0.936	0.724	0.658	0.440	0.532	0.480	0.439	0.553	1.077
	γ	-0.901	11.299	39.943	-27.720	-18.378	-62.329	-51.938	-6.475	-0.422
Log-Logistic (6-month)	α	6.455	5.525	10.090	7.036	7.457	6.168	6.915	5.140	8.548
	β	991.470	685.500	1236.800	1116.400	1027.100	1273.500	1528.900	861.620	0.045
	γ	-1162.100	-709.780	-1409.300	-1150.900	-1126.100	-965.560	-1432.400	-971.440	-5593.200
Lognormal (12-month)	μ	4.853	6.024	7.423	5.592	6.662	7.199	7.422	5.192	5.486
	σ	0.447	0.292	0.182	0.192	0.098	0.132	0.049	0.163	0.590
	γ	-25.568	-20.657	-729.730	-67.318	-551.100	-352.480	-1216.800	-107.080	7.127
Log-Logistic (12-month)	α	7.479	8.206	8.242	8.319	19.985	14.607	13.114	42.761	22.868
	β	899.160	0.047	0.040	872.190	2293.900	1891.400	1640.800	5621.600	2409.100
	γ	-1208.400	-3656.900	-4117.900	-907.640	-2456.100	-1214.600	-1394.000	-5768.200	-3277.400

and lastly returns the quantile of the standard normal distribution.

The SPERI considers the integrated impacts of precipitation, evapotranspiration and runoff on drought. P-PET denotes the usable amount of precipitation after deducting potential evapotranspiration (a positive value denotes a surplus, and a negative value denotes a deficit). Whether the area experiences drought depends on the analysis of runoff. For example, precipitation in a certain region in some periods is small with very large PET, but a river flows through the region. Because of upstream snow melt or water reservoir discharges, drought due to meteorological elements (precipitation and evaporation) would be buffered by hydrological elements (runoff). This is because when a

drought occurs, river water can be used to fight it. Therefore, it is necessary to develop a drought index considering runoff. This will provide a basis for relevant departments to develop plans for fighting drought and drought relief.

2. Data and methods

2.1. Study area and data

This article chose Yunnan Province in China (Fig. 1) as an example to calculate, analyze and evaluate SPERI. Located in the southwestern

Table 2
Kendall rank correlation coefficient at different temporal scales and parameters of the Copula functions.

time scale	Parameter	Chuxiong	Guangnan	Huize	Jinghong	Longyang	Pingbian	Ruili	Shilin	Yuanmou
1-month	Kendall τ	0.548	0.526	0.572	0.573	0.605	0.585	0.594	0.570	0.474
	GH-Copula θ	2.213	2.107	2.334	2.344	2.528	2.409	2.463	2.327	1.901
	Clayton Copula θ	2.427	2.215	2.669	2.687	3.057	2.818	2.926	2.654	1.802
	Frank Copula θ	6.689	6.220	7.217	7.257	8.051	7.540	7.772	7.186	5.281
3-month	Kendall τ	0.623	0.652	0.651	0.649	0.693	0.684	0.650	0.627	0.525
	GH-Copula θ	2.649	2.873	2.862	2.850	3.257	3.167	2.857	2.682	2.106
	Clayton Copula θ	3.298	3.745	3.724	3.700	4.515	4.333	3.714	3.363	2.212
	Frank Copula θ	8.563	9.503	9.458	9.407	11.098	10.724	9.438	8.701	6.214
6-month	Kendall τ	0.653	0.663	0.627	0.655	0.687	0.706	0.643	0.628	0.450
	GH-Copula θ	2.885	2.966	2.682	2.901	3.199	3.406	2.803	2.691	1.819
	Clayton Copula θ	3.770	3.931	3.363	3.802	4.398	4.812	3.605	3.382	1.638
	Frank Copula θ	9.555	9.890	8.701	9.621	10.858	11.710	9.210	8.740	4.897
12-month	Kendall τ	0.524	0.523	0.430	0.484	0.527	0.493	0.318	0.572	-0.019
	GH-Copula θ	2.102	2.097	1.753	1.939	2.112	1.972	1.466	2.336	0.981
	Clayton Copula θ	2.204	2.194	1.507	1.877	2.225	1.943	0.932	2.672	-0.037
	Frank Copula θ	6.196	6.173	4.585	5.456	6.242	5.607	3.123	7.224	-0.171

Table 3
Testing and assessment of the different Copula functions.

Method	Time scale	Catalog	Chuxiong	Guangnan	Huize	Jinghong	Longyang	Pingbian	Ruili	Shilin	Yuanmou
OLS	1-month	GH-Copula	0.048	0.046	0.058	0.046	0.064	0.056	0.054	0.050	0.053
		Clayton Copula	0.048	0.047	0.053	0.042	0.059	0.046	0.047	0.043	0.050
		Frank Copula	0.044	0.043	0.054	0.041	0.059	0.049	0.049	0.044	0.048
	3-month	GH-Copula	0.041	0.042	0.049	0.044	0.049	0.054	0.049	0.047	0.042
		Clayton Copula	0.038	0.039	0.042	0.035	0.040	0.042	0.039	0.037	0.034
		Frank Copula	0.037	0.038	0.046	0.039	0.044	0.049	0.044	0.043	0.037
	6-month	GH-Copula	0.040	0.045	0.052	0.039	0.042	0.052	0.053	0.044	0.047
		Clayton Copula	0.034	0.041	0.047	0.032	0.035	0.042	0.043	0.036	0.040
		Frank Copula	0.037	0.042	0.050	0.036	0.040	0.049	0.050	0.041	0.044
	12-month	GH-Copula	0.052	0.043	0.106	0.048	0.050	0.064	0.050	0.054	0.061
		Clayton Copula	0.050	0.047	0.107	0.049	0.049	0.063	0.056	0.054	0.055
		Frank Copula	0.048	0.042	0.107	0.046	0.047	0.063	0.051	0.051	0.059
K-S	1-month	GH-Copula	0.143	0.109	0.155	0.142	0.174	0.156	0.152	0.133	0.146
		Clayton Copula	0.143	0.114	0.130	0.124	0.159	0.129	0.133	0.119	0.136
		Frank Copula	0.131	0.096	0.139	0.125	0.157	0.139	0.136	0.115	0.130
	3-month	GH-Copula	0.117	0.112	0.138	0.111	0.133	0.135	0.119	0.124	0.105
		Clayton Copula	0.098	0.100	0.101	0.086	0.101	0.099	0.094	0.090	0.085
		Frank Copula	0.100	0.094	0.127	0.099	0.118	0.124	0.103	0.109	0.090
	6-month	GH-Copula	0.111	0.108	0.145	0.108	0.111	0.134	0.126	0.119	0.122
		Clayton Copula	0.077	0.092	0.109	0.080	0.083	0.096	0.094	0.083	0.094
		Frank Copula	0.101	0.099	0.133	0.095	0.101	0.128	0.114	0.109	0.113
	12-month	GH-Copula	0.135	0.110	0.264	0.114	0.134	0.172	0.121	0.135	0.178
		Clayton Copula	0.141	0.117	0.265	0.128	0.117	0.160	0.135	0.135	0.148
		Frank Copula	0.119	0.100	0.265	0.105	0.117	0.159	0.114	0.121	0.162

part of China, Yunnan Province is mainly affected by the plateau monsoon climate, which makes most of the areas characterized by warm in winter and cool in summer. In addition, due to the control and influence of different atmospheric circulations, the precipitation is unevenly distributed in spatial, and the dry and wet seasons are obvious in temporal.

In order to calculate SPERI, this article selected the monthly precipitation, temperature, relative humidity, sunshine hours, wind speed and runoff data of 9 stations in Yunnan Province (Fig. 1). The above data came from the Yunnan Meteorological Bureau and Hydrological Bureau. And, this article also selected the extreme drought grades during September 2009–August 2010 provided by the Yunnan Flood Control and Drought Relief Office to assess the accuracy of SPERI.

2.2. Methods

This study first calculates PET in each period using the Penman-Monteith (PM) formula according to meteorological data, then uses the Copula function to calculate the joint distribution function of P-PET and runoff, and finally transforms the probability of the joint distribution function into the quantile of the standard normal distribution

function, which is SPERI.

2.2.1. Potential evapotranspiration

The SPEI uses the Thornthwaite method to calculate PET. This method is simple and only requires small types of data. However, relevant studies have shown that the global drying trend of the past 60 years is overestimated (Hulme, 1996; IPCC, 2007; Sheffield et al., 2012), which is caused by use of the Thornthwaite empirical formula to calculate PET so that PET is overestimated (Sheffield et al., 2012). Therefore, this study uses the PM method (Allen et al., 1998) recommended by the Food and Agriculture Organization of the United Nations to calculate PET. This method is more complicated and requires more data, but with more accurate results.

The SPERI uses a month as the calculation duration, selects data that include temperature, relative humidity, sunshine hours, and wind speed and calculates the PET of each station in each month and year using the ETo calculator published by FAO.

2.2.2. P-PET and runoff

According to the monthly precipitation for each year and PET calculated above, their differences are

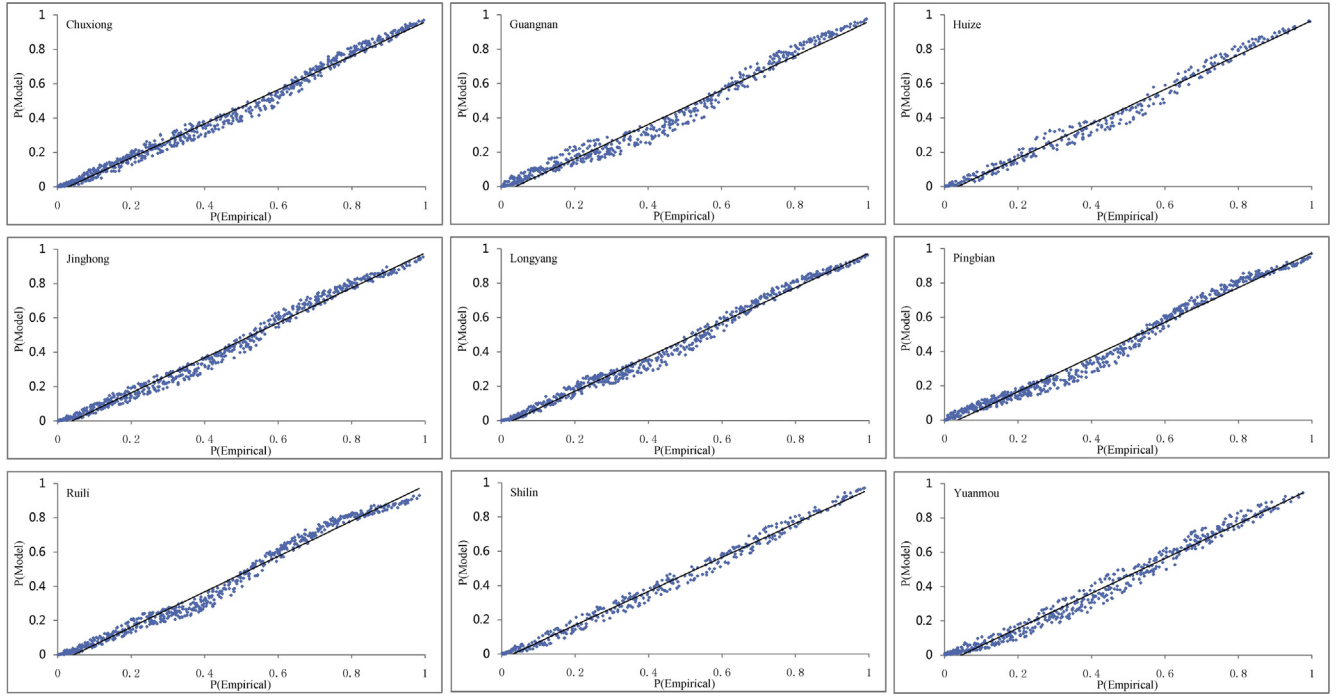


Fig. 10. P-P plot of SPERI at a temporal scale of 1 month.

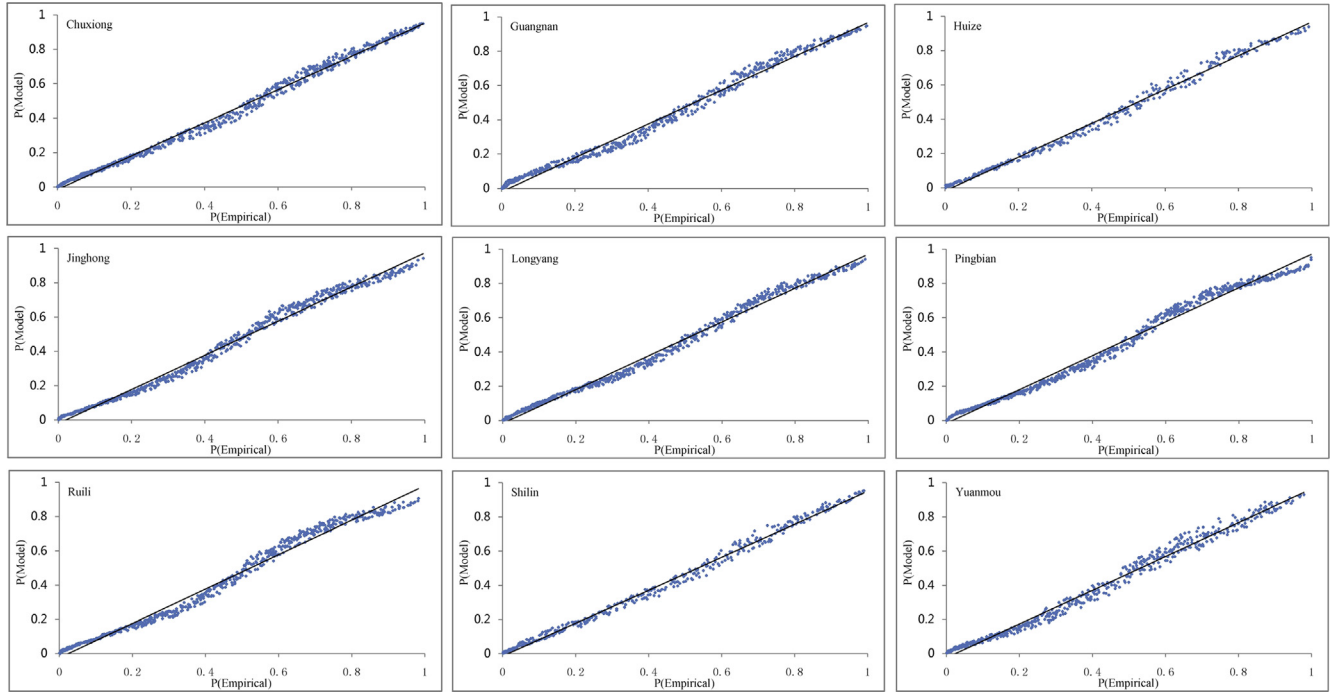


Fig. 11. P-P plot of SPERI at a temporal scale of 3 months.

$$D_{i,j} = P_{i,j} - PET_{i,j} \quad (1)$$

where $P_{i,j}$ denotes precipitation of the i th year and j th month, and $PET_{i,j}$ denotes the potential evapotranspiration of the i th year and j th month.

According to Eq. (1), the total amount of each different temporal scale $X_{i,j}^k$ (k denotes the temporal scale) is calculated using the same method as for SPI and SPEI.

$$D_l = D_{i,j} \quad l = (i - i_0) \times 12 + j \quad (2)$$

$$X_l^k = \sum_{l=k+1}^l D_l \quad (3)$$

$$X_{i,j}^k = X_l^k \quad i = i_0 + \text{int}[(l - 1)/12] \quad j = \text{mod}[(l - 1), 12] + 1 \quad (4)$$

where l is the order number, i_0 is the initial year, $\text{int}[(l - 1)/12]$ represents the integer part of $(l - 1)/12$, and $\text{mod}[(l - 1), 12]$ represents the modulo of $(l - 1)/12$.

The method used to calculate the total runoff amount of each different temporal scale is the same as that for P-PET.

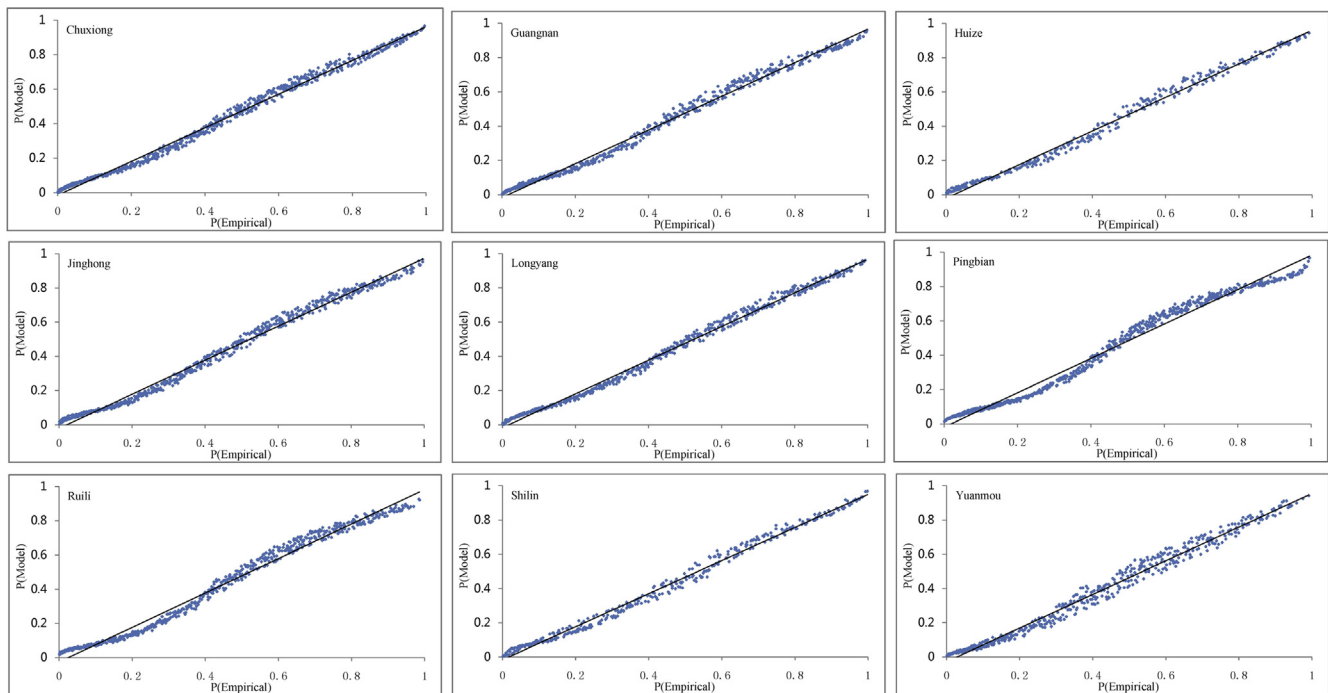


Fig. 12. P-P plot of SPERI at a temporal scale of 6 months.

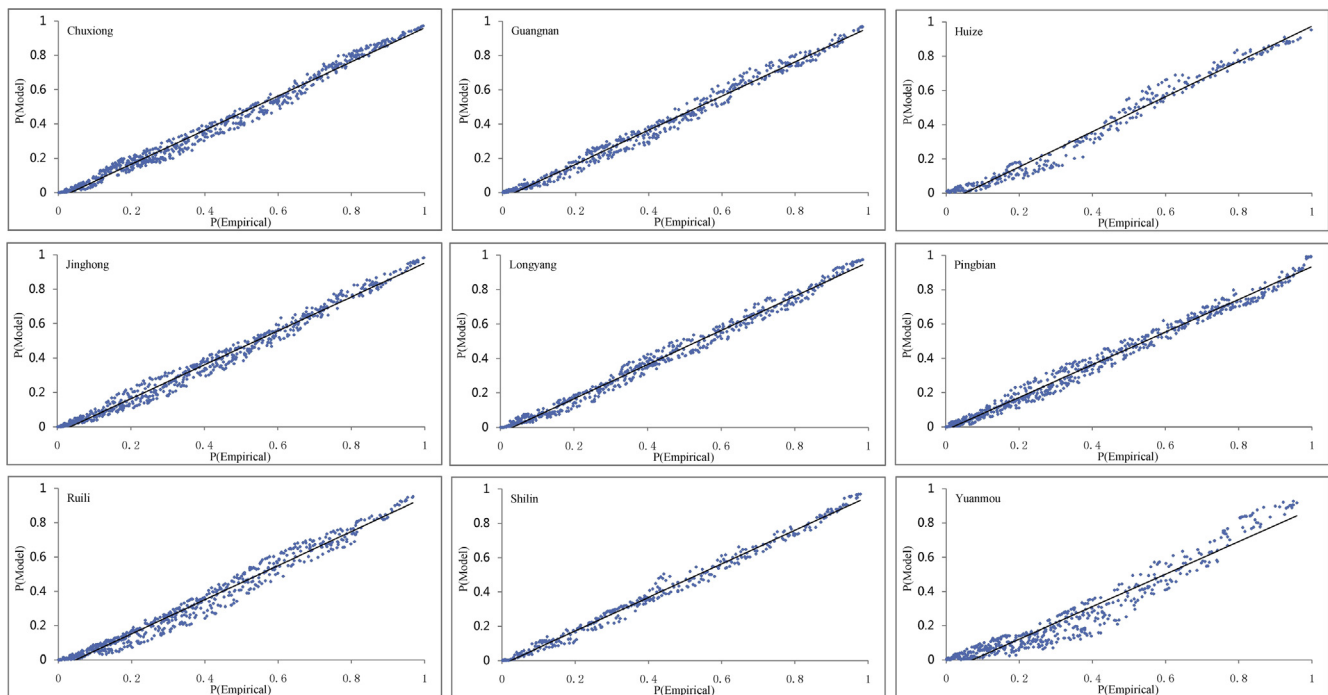
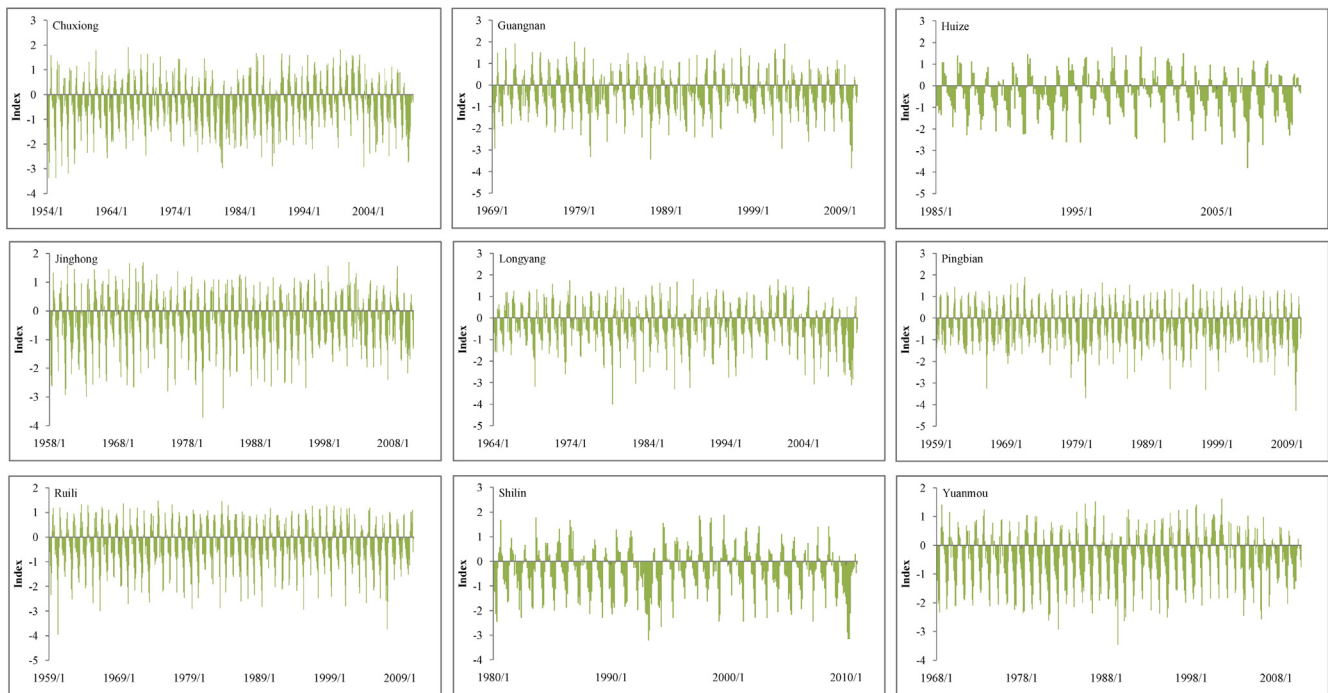
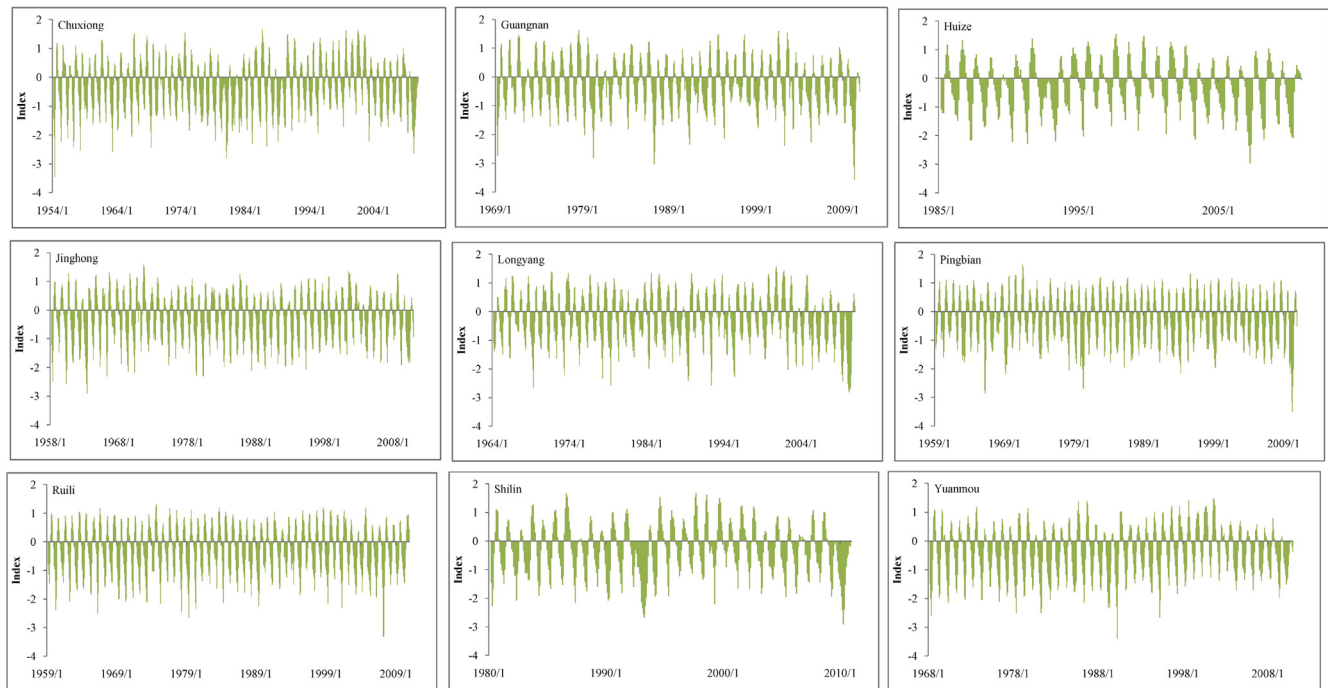


Fig. 13. P-P plot of SPERI at a temporal scale of 12 months.

2.2.3. The joint distribution function of P-PET and runoff

Because univariate frequency analyses cannot completely solve the problems encountered in actual work, multivariate frequency analyses are drawing increased attention. Early multivariate frequency analyses primarily employed the following methods: (1) multivariate normal distributions (Correia, 1987; Sackl and Bergmann, 1987; Goel et al., 1988; Yue, 2000a; Bonaccorso et al., 2015), (2) joint distributions consisting of specific margin distributions (Bacchi et al., 1994; Yue, 2000b, 2001) and (3) non-parametric methods (Silverman, 1986; Lau and Bosworth, 1994). All the above methods suffer problems. For

example, assuming or transforming original data to a normal distribution is complicated and easily distorted, and different hydrological variables may obey different distribution types. In addition, the margin distribution types of the joint distribution constructed using non-parametric methods are unknown (Guo et al., 2008). To address the above problems, many scholars have applied the Copula function theory and method to multivariable hydrological analyses and calculations (Shiau, 2006; Serinaldi et al., 2009; Song and Singh, 2010; Chen et al., 2015; Xu et al., 2015; Bezak et al., 2016; Chang et al., 2016; Papaioannou et al., 2016; Balistrocchi and Bacchi, 2017; Zhang et al., 2017; Lei et al.,

Fig. 14. SPERI₁ at a temporal scale of 1 month.Fig. 15. SPERI₃ at a temporal scale of 3 months.

2017).

Therefore, the SPERI uses the Copula function for calculations. The details are as follows.

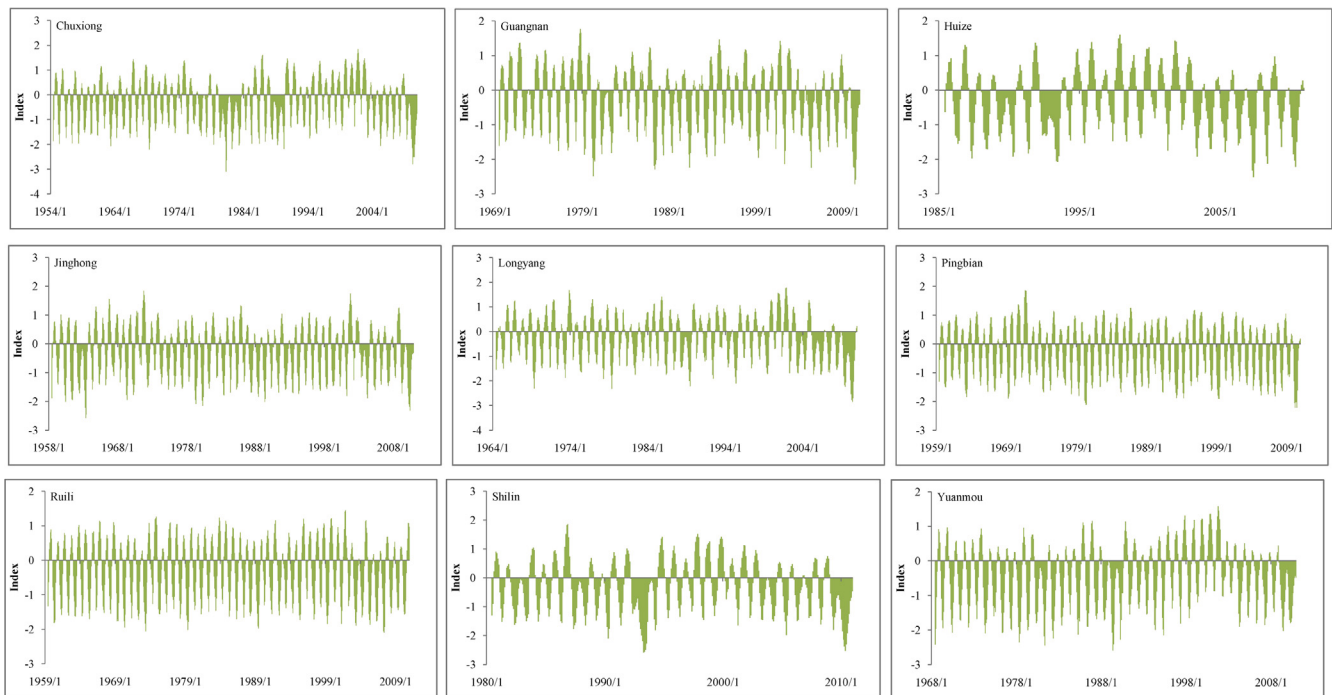
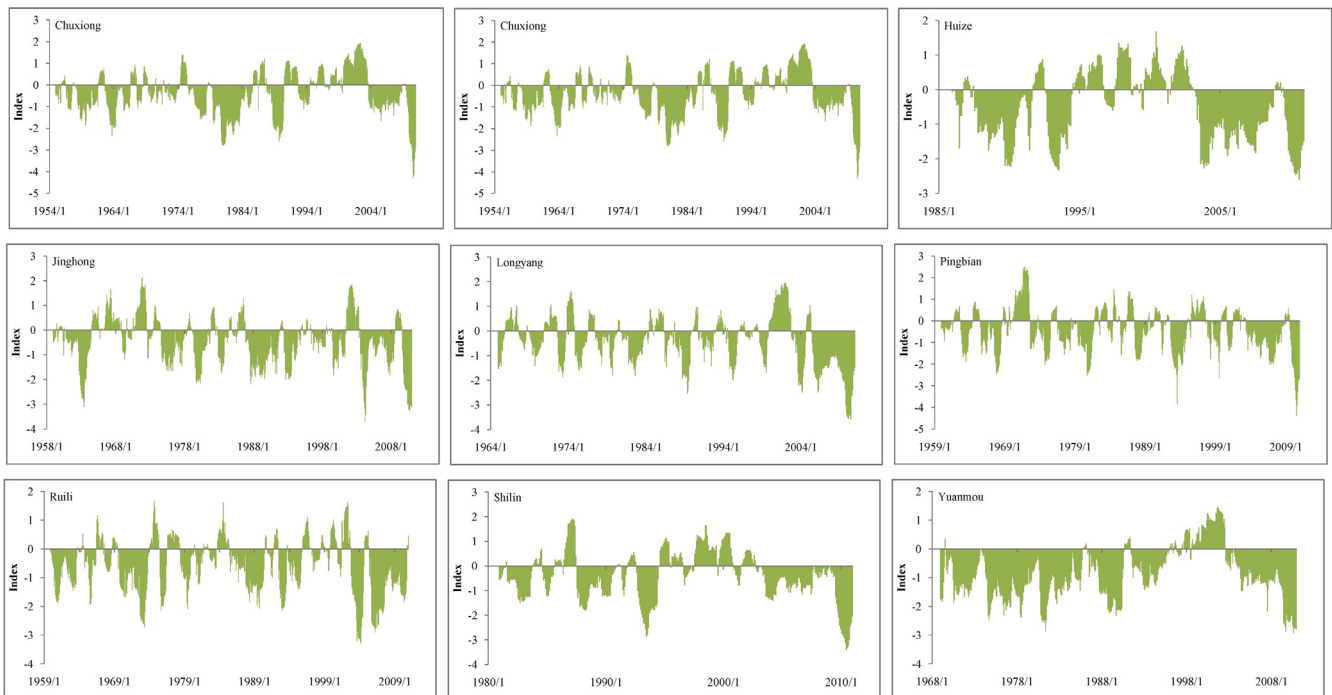
Sklar (1959) proved that the margin distributions $F_1(x_1), F_2(x_2), \dots, F_n(x_n)$ of the joint distribution function $H(x_1, x_2, \dots, x_n)$ with multiple random variables $X_1, X_2, \dots, X_n$ are continuous, and only one Copula function C then satisfies the following equation:

$$H(x_1, x_2, \dots, x_n) = C(F_1(x_1), F_2(x_2), \dots, F_n(x_n)) \quad (5)$$

The joint distribution function consists of two parts, the margin distribution and the correlation structure, that can be described by the

Copula function. Overall, the construction of the Copula function includes the following steps: (1) determine the margin distribution of each variable, (2) determine the parameters of the Copula function, (3) select the Copula function according to the assessment index and build a joint distribution and (4) conduct the corresponding statistical analysis according to the established distribution (**Guo et al., 2008**). Because the SPERI is based on two variables, P-PET and Runoff, the calculation process of the 2-dimensional Copula function will be discussed below.

2.2.3.1. Margin distribution. The probability density functions of runoff

Fig. 16. SPERI₆ at a temporal scale of 6 months.Fig. 17. SPERI₁₂ at a temporal scale of 12 months.

(X) and P-PET (Y) are fitted separately to obtain the corresponding distribution functions $F(x)$ and $F(y)$. Because runoff and P-PET differ around the globe, this study does not recommend a specific type of margin distribution function.

2.2.3.2. Correlation coefficient. At present, the most widely used correlation indexes for hydrological variables are the Pearson linear correlation coefficient and the Kendall rank correlation coefficient (Nelsen, 2006). The Kendall rank correlation coefficient can describe the nonlinear correlation between variables as well as the linear

correlation between variables (Guo et al., 2008). It is defined as

$$\tau = (C_n^2)^{-1} \sum_{i < j} \text{sign}[(x_i - x_j)(y_i - y_j)] \quad i, j = 1, 2, \dots, n \quad (6)$$

where (x_i, y_i) are the sample data, and $\text{sign}(\cdot)$ is the sign function.

2.2.3.3. Copula function. Generally, the Copula function can be divided into three types: Elliptic, Archimedean and quadratic. Nelsen (2006) described in detail the widely used Archimedean Copula functions and their properties. Therefore, SPERI only selects the following few

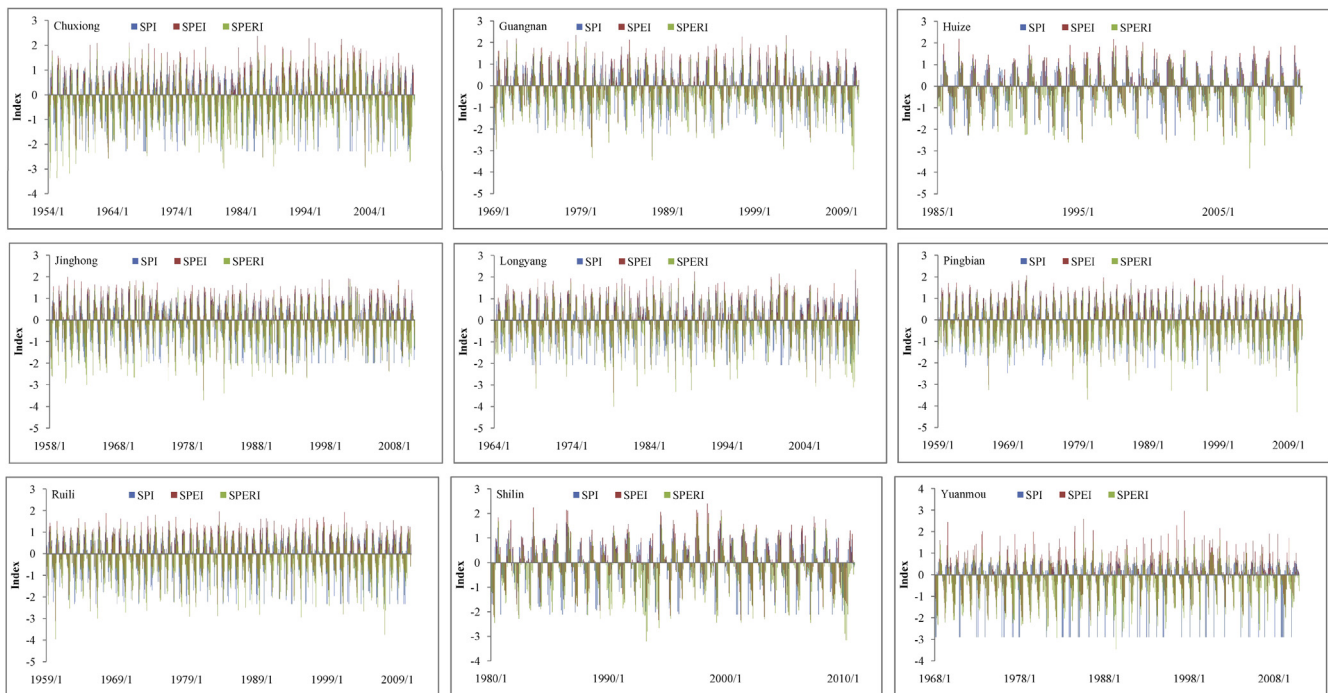


Fig. 18. SPI/SPEI/SPERI at a temporal scale of 1 month.

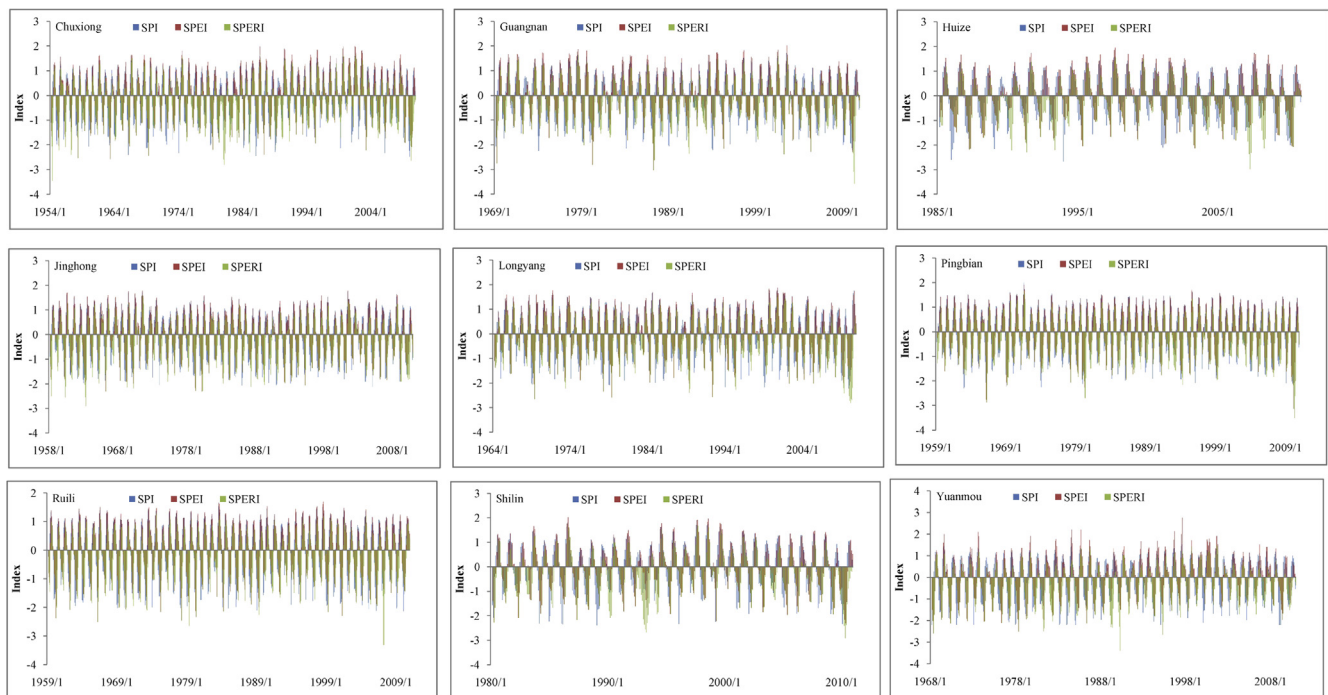


Fig. 19. SPI/SPEI/SPERI at a temporal scale of 3 months.

commonly-used two-dimensional Archimedean Copula functions in hydrology and relevant fields.

1) Gumbel-Hougaard (GH) Copula function. The structures of the GH-Copula function and the Gumbel logistic model (Yue, 2001) are the same:

$$C(u, v) = \exp\left\{-[(-\ln u)^\theta + (-\ln v)^\theta]^{1/\theta}\right\} \theta \in [1, \infty) \quad (7a)$$

where u, v denote the margin distribution functions $u = F(x)$ and $v = F(y)$, respectively, and they have the same meanings in later equations. θ denotes a parameter of the GH-Copula function, and it has

the same meanings in later equations. Its relationship with the Kendall rank correlation coefficient is

$$\tau = 1 - \frac{1}{\theta} \quad (8a)$$

2) Clayton Copula function. The Equation of the Clayton Copula function is

$$C(u, v) = (u^{-\theta} + v^{-\theta} - 1)^{-1/\theta} \theta \in (0, \infty) \quad (7b)$$

The relationship between θ and τ is

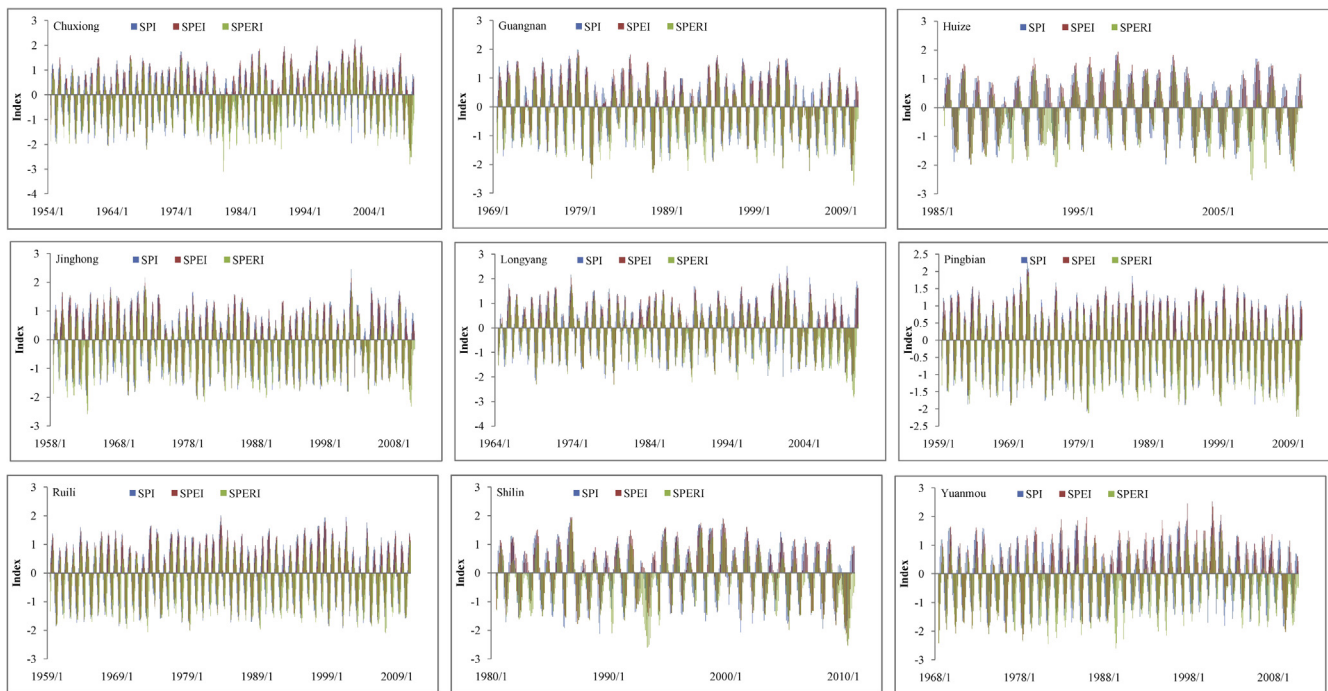


Fig. 20. SPI/SPEI/SPERI at a temporal scale of 6 months.

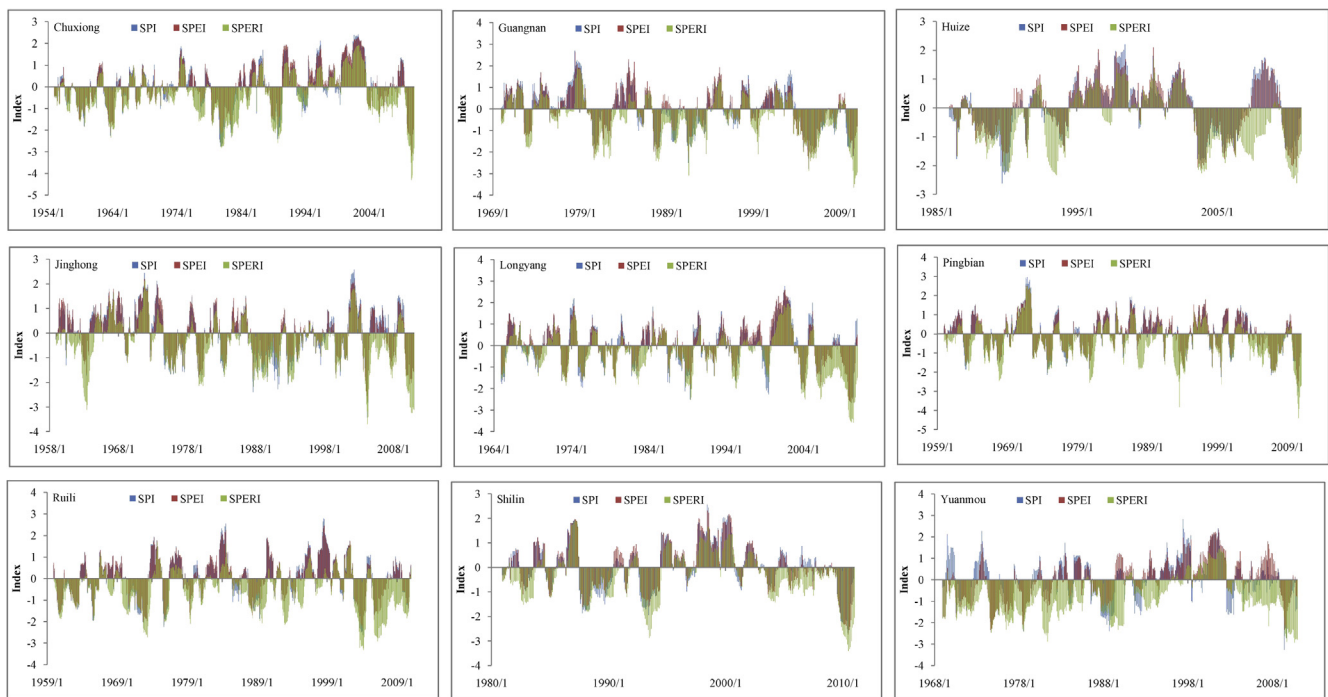


Fig. 21. SPI/SPEI/SPERI at a temporal scale of 12 months.

$$\tau = \frac{\theta}{2 + \theta}$$

(8b)

3) Frank Copula function. The Frank Copula Equation is

$$C(u, v) = -\frac{1}{\theta} \ln \left[1 + \frac{(e^{-\theta u} - 1)(e^{-\theta v} - 1)}{(e^{-\theta} - 1)} \right] \quad \theta \in R$$

(7c)

The relationship between θ and τ is

$$\tau = 1 + \frac{4}{\theta} \left[\frac{1}{\theta} \int_0^\theta \frac{t}{\exp(t) - 1} dt - 1 \right]$$

(8c)

2.2.3.4. Joint probability. According to the margin distributions of the two variables and the joint probability of the two-dimension Copula function obtained by Eqs. (7a)–(8c), the Equation is

$$P(X \leq x, Y \leq y) = C(x, y) \quad (9)$$

where x and y are a pair of measured values for R and P -PET.

2.2.3.5. Assessment and testing of the goodness of fit of the Copula function. Which Copula function should be chosen? Under the condition with measured data, the type of Copula function that best

Table 4
Correlation coefficients between SPI/SPEI/SPERI.

	Chuxiong	Guangnan	Huize	Jinghong	Longyang	Pingbian	Ruili	Shilin	Yuanmou
SPI ₁ vs. SPEI ₁	0.7408	0.8031	0.7241	0.8433	0.8088	0.9094	0.7752	0.8218	0.4424
SPI ₃ vs. SPEI ₃	0.8073	0.8502	0.7784	0.9071	0.8566	0.9478	0.9011	0.8527	0.7005
SPI ₆ vs. SPEI ₆	0.8977	0.9301	0.8842	0.9559	0.9222	0.9826	0.9782	0.9266	0.7684
SPI ₁₂ vs. SPEI ₁₂	0.9592	0.9546	0.9588	0.9602	0.9499	0.9871	0.9823	0.9721	0.8228
SPI ₁ vs. SPERI ₁	0.7331	0.7145	0.6206	0.7105	0.7005	0.8185	0.6370	0.7545	0.4144
SPI ₃ vs. SPERI ₃	0.8149	0.7782	0.6992	0.8006	0.7841	0.8743	0.7878	0.7986	0.7063
SPI ₆ vs. SPERI ₆	0.8825	0.8699	0.8033	0.8739	0.8491	0.9335	0.8968	0.8659	0.7697
SPI ₁₂ vs. SPERI ₁₂	0.9235	0.9033	0.8028	0.8646	0.8651	0.8841	0.7943	0.9043	0.6298
SPEI ₁ vs. SPERI ₁	0.9224	0.9103	0.9144	0.9152	0.9386	0.9385	0.9138	0.9201	0.8785
SPEI ₃ vs. SPERI ₃	0.9360	0.9449	0.9326	0.9461	0.9597	0.9574	0.9376	0.9279	0.9157
SPEI ₆ vs. SPERI ₆	0.9463	0.9536	0.9285	0.9556	0.9583	0.9680	0.9520	0.9302	0.9012
SPEI ₁₂ vs. SPERI ₁₂	0.9349	0.9177	0.8484	0.9112	0.9296	0.9005	0.8436	0.9376	0.6980

Note: the subscript in the table denotes temporal scale.

Table 5
Drought grades.

Level	Drought Category	SPI, SPEI, SPERI Values
0	Non-drought	−0.5 < Index
1	Mild drought	−1.0 < Index ≤ −0.5
2	Moderate drought	−1.5 < Index ≤ −1.0
3	Severe drought	−2.0 < Index ≤ −1.5
4	Extreme drought	Index ≤ −2.0

fits the data is chosen.

1) Assessment of the goodness of fit of the Copula function

The assessment index of goodness of fit is an important criterion for selecting the distribution type. Here, this article use Ordinary Least Squares (OLS) to assess the goodness of fit of different Copula functions. The Equation is

$$OLS = \sqrt{\frac{1}{n} \sum_{i=1}^n (pe_i - p_i)^2} \quad (10)$$

where pe_i and p_i denote the empirical and theoretical frequencies, respectively. Fit improves with smaller OLS.

2) Testing the goodness of fit of the Copula function

To validate whether the selected Copula function is able to describe the correlation structure among the variables, it is necessary to validate the fit of the Copula function. This study selects the Kolmogorov-Smirnov (K-S) test to assess the fitness degree between the joint distribution and joint observations. The statistic D is calculated as

$$D = \max |pe_i - p_i| \quad (11)$$

The bivariate empirical frequency can be derived using the theoretical basis of the univariate empirical frequency (Gringorten, 1963; Cunnane, 1978), for which the mathematical expression is

$$P(X \leq x, Y \leq y) = \frac{\sum_{m=1}^i \sum_{l=1}^j n_{ml} - 0.44}{N + 0.12} \quad (12)$$

where N denotes the number of data, and n_{ml} is the order number of $X \leq x_i, Y \leq y_j$.

2.2.4. Calculation of the SPERI

The SPERI is obtained by transforming the above calculated verified joint distribution probability to a standard normal distribution; the approximate Equation is

$$SPERI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \quad (13)$$

where $W = \sqrt{-2 \ln(P)}$ for $P \leq 0.5$, P is the probability of exceeding a determined D value, and $P = 1 - C$. If $P > 0.5$, then P is replaced by $P = 1 - P$, and the sign of the resultant SPERI is reversed. The

constants are $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$.

3. Results

The SPERI was calculated in Yunnan Province. First, this article selected monthly precipitation, temperature, relative humidity, sunshine hours, wind speed and runoff data from the 9 stations (Fig. 1) in Yunnan Province and then used the above calculation method to obtain the SPERI. The purpose of this study is to propose a drought index. Therefore, the calculation temporal scales are 1, 3, 6, 12 months, and the calculation methods for the other temporal scales are similar.

3.1. Fitting probability density function

First, this article calculated P-PET (PET is based on the PM calculation method) and runoff in the different temporal scales, and then fit their probability density functions. Because P-PET and runoff do not know what to follow the distributions, this article selected dozens of distribution functions and used the method of maximum likelihood estimation to estimate parameters of the different distribution functions (the calculation method is given in Chen (1996)). According to the above steps, this article finally selected the Log-Logistic distribution [Cumulative Distribution Function (CDF): $F(x) = \left(1 + \left(\frac{\beta}{x - \gamma}\right)^\alpha\right)^{-1}$], where α , β and γ are CDF parameters] for the P-PET and Lognormal distribution [CDF: $F(x) = \Phi\left(\frac{\ln(x - \gamma) - \mu}{\sigma}\right)$], where Φ is the Laplace Integral, and μ , σ and γ are CDF parameters] for runoff. Figs. 2–9 show the empirical probability-theoretical probability (P-P) plot, which is nearly a line. This suggests that the distribution function is able to fit P-PET and runoff data of different temporal scales very well. The parameters of the distribution functions are provided in Table 1.

3.2. Joint distribution function

First, according to Eqs. (6) and (8a)–(8c), this article calculated the Kendall rank correlation coefficient and the parameters of the Copula function (Table 2), calculated the values of the three types of Copula functions according to Eqs. (7a)–(7c), and finally selected the most suitable Copula function (Table 3) according to the assessment and testing of the three Copula functions using Eqs. (10)–(12).

Table 3 shows that the Frank Copula function was selected for the temporal scale of 1, 12 months and that the Clayton Copula function was selected for the temporal scale of 3, 6 months. Most of the K-S testing values of these two functions are smaller than the thresholds. Thus, the assumed testing is satisfied. Therefore, for this example, the Frank and Clayton Copula distribution functions were selected for the temporal scales of 1, 12 months and 3, 6 months, respectively. The P-P plots are shown in Figs. 10–13.

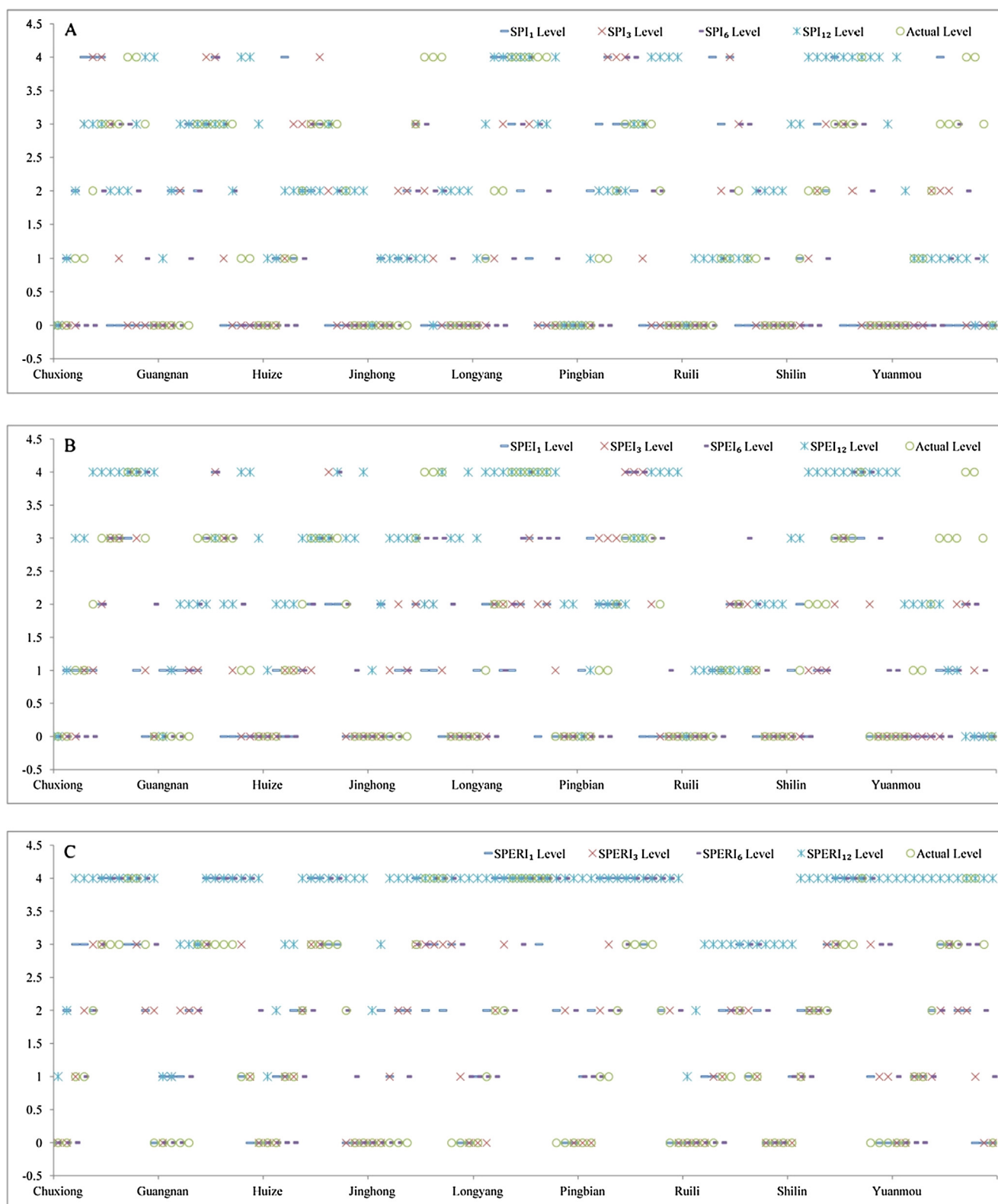


Fig. 22. Comparison of the SPI, SPEI and SPERI grades with the actual drought grades during September 2009–August 2010 at temporal scales of 1, 3, 6, 12 months. Note: the actual drought grades are defined based on some survey on observed drought impacts over the whole region. Whether drought occurs is mainly determined by investigating crop morphological characteristics. According to the standard, the upper part of the crop leaves are rolled up due to drought, it is determined to be mild drought. If the leaves cause wilting during the day due to drought, it is judged to be moderate drought. The seedlings of crop are dead due to drought, the leaves are withered, and the fruits fall off, which is judged to be severe drought. If the plants are dead due to drought, it is judged to be extreme drought.

Table 6
Assessment of SPI/SPEI/SPERI.

	SPI ₁	SPI ₃	SPI ₆	SPI ₁₂	SPEI ₁	SPEI ₃	SPEI ₆	SPEI ₁₂	SPERI ₁	SPERI ₃	SPERI ₆	SPERI ₁₂
Rate of absolute accurate	37.96%	45.37%	48.15%	25.00%	39.81%	44.44%	44.44%	24.07%	41.67%	50.93%	42.59%	12.96%
Rate of relative accurate	20.37%	28.70%	26.85%	40.74%	28.70%	36.11%	27.78%	38.89%	37.04%	32.41%	30.56%	48.15%
Rate of Wrong	41.67%	25.93%	25.00%	34.26%	31.48%	19.44%	27.78%	37.04%	21.30%	16.67%	26.85%	38.89%

Table 7

The percentage of SPI, SPEI and SPERI drought grades less than or greater than actual drought grades during September 2009–August 2010.

	SPI ₁	SPI ₃	SPI ₆	SPI ₁₂	SPEI ₁	SPEI ₃	SPEI ₆	SPEI ₁₂	SPERI ₁	SPERI ₃	SPERI ₆	SPERI ₁₂
–	5.56%	12.04%	20.37%	19.44%	22.22%	25.00%	16.67%	10.19%	8.33%	10.19%	12.04%	0
+	14.81%	16.67%	6.48%	21.30%	6.48%	11.11%	11.11%	28.70%	28.70%	22.22%	18.52%	48.15%

Note: “–” (“+”) denotes SPI, SPEI and SPERI grades less (greater) than the actual drought grades.

3.3. Calculation of the SPERI

This article used Eq. (13) to transform the above-calculated Copula joint distribution probability into the quantile of the standard normal distribution, which is the SPERI, as shown in Figs. 14–17.

3.4. Comparison of the SPERI to the SPI and SPEI

This article used two methods to assess the SPERI: one was to calculate the SPI and SPEI using precipitation and P-PET and a comparison of the three indexes (as Figs. 18–21), and the other was to use data for the extreme drought during September 2009–August 2010 in Yunnan province to validate the accuracy of the SPERI.

Figs. 18–21 show that the changes in the SPERI were similar to those in the SPI and SPEI (Table 4). In addition, Table 4 shows that the SPERI was well correlated to the SPI and SPEI. The correlation between the SPEI and SPERI was the best, followed by the correlation between the SPI and SPEI, suggesting that SPERI is used to describe drought conditions. Additionally, most of the SPEI values exceed the SPI and SPERI values, suggesting that drought intensity may be smaller than the actual drought intensity after consideration of PET, and most of the SPERI values are smaller than the SPI and SPEI values, drought intensity may be greater than the actual drought intensity due to the consideration of not only P-PET difference but also the impact of runoff on drought. As for fighting drought and drought relief, people prefer forecasted drought intensities greater than the actual intensities under most conditions, which is more favorable for making plans to fight drought and for drought relief. Therefore, it is feasible to use SPERI analysis assessments to forecast droughts.

In addition, this article used the extreme drought grades during September 2009–August 2010 provided by the Yunnan Flood Control and Drought Relief Office to assess the accuracy of the three drought indexes. First, according to the China national standard *Grades of Meteorological Drought* (GB/T 20481-2017) (General Administration of Quality Supervision, 2017), the values of the SPI, SPEI and SPERI were divided into five grades (because the calculation principles of the SPERI are similar to those of the SPI and SPEI, the SPERI uses the same grade standard as the SPI and SPEI, as shown in Table 5), and then compared the grades of the three drought indexes of the 9 stations at temporal scales of 1, 3, 6, 12 months with the provided actual drought grades, as shown in Fig. 22. Fig. 22 shows that for the total of 108 counts (12 months $\times$ 9 stations), the number of absolute accurate assessments (absolute accurate assessment: the calculated drought grade completely matches the actual drought grade) of SPI₁, SPI₃, SPI₆, SPI₁₂, SPEI₁, SPEI₃, SPEI₆, SPEI₁₂, SPERI₁, SPERI₃, SPERI₆ and SPERI₁₂ were 41, 49, 52, 27, 43, 48, 48, 26, 45, 55, 46 and 14, respectively; the number of relative accurate assessments (relative accurate assessment: the calculated index and reality show drought concurrently, but the calculated drought grade is higher or lower than the actual drought grade) was 22,

31, 29, 44, 31, 39, 30, 42, 40, 35, 33 and 52, respectively; and the number of wrong assessments (wrong assessment: the calculated indexes indicate drought, but no actual drought occurs, or an actual drought occurs, whereas the calculated indexes do not suggest drought) was 45, 28, 27, 37, 34, 21, 30, 40, 23, 18, 29 and 42, respectively. Overall, the assessment with a temporal scale of 3 months was more accurate than the other temporal scales. In addition, regardless of whether an absolute accurate assessment or relative accurate assessment, the SPERI was superior to the other two drought indexes. The SPERI with a temporal scale of 3 months was also able to identify the drought very well, as shown in Table 6.

4. Discussion and conclusions

According to precipitation, temperature, relative humidity, sunshine hours, wind speed and runoff data, this study uses methods that include PM and Copula and the calculation principles of the SPI and SPEI to propose a multi-scalar drought index (the standardized precipitation evapotranspiration runoff index, SPERI). This article applied the index to Yunnan province and compared it with the widely used SPI and SPEI. The results show that the SPERI is superior to the SPI and SPEI.

Although for multi-year averages and closed watersheds, precipitation minus evapotranspiration is equal to runoff, what people care about is the analysis, assessment and forecasting of drought conditions of a specific area in a certain period. Therefore, the consideration of the two variables of P-PET and runoff in this index is reasonable. That is, except for meteorological factors, the SPERI also considers the impact of hydrological factors on drought. Therefore, the SPERI can be considered as a hydrological drought index or a simple drought disaster index (when a drought disaster occurs, river water can be fetched to relieve the drought). Similar to the SPEI, the SPERI is capable of describing the drought conditions of different areas and assessing the impacts of climate change on drought.

Because the conditions of different areas are not always the same, different from other drought indexes that specify a certain probability distribution, the bivariate distribution of the SPERI does not specify any probability distribution; rather it selects the distribution with the best fitting results. Similarly, the joint distribution probability can be calculated with other Copula functions, whereas it needs to pass assessments and tests of goodness of fit.

When applying the three indexes to Yunnan Province, this article found that the changes in the SPERI were similar to those in the SPI and SPEI and were well correlated across the indexes. This suggests that the SPERI can also reflect regional drought conditions. In addition, the comparison between the three drought index grades and the actual grades of the extreme drought during September 2009–August 2010 shows that the SPERI is superior to the SPI and SPEI and that the SPERI assessment at a temporal scale of 3 months was the most accurate.

Figs. 18–21 show that the SPEI was overestimated, whereas the SPERI value was underestimated, suggesting that the drought intensity assessed by the SPEI may be smaller than the actual drought intensity and that assessed by the SPERI may be greater than the actual intensity. This conclusion is consistent with Table 7. Under conditions for which there is no accurate forecast, people prefer a forecasted drought grade higher than the actual drought grade, which is favorable for making plans for drought prevention and relief. In summary, the SPERI method is reasonable and enhances the accuracy of drought assessments to some extent.

In addition, we have also developed automatic calculation software for multi-temporal scalar, executable SPERI. Please contact the first author or the corresponding author if necessary.

Acknowledgements

This study was supported by the Science and Technology Project of Yunnan Province (2014FD022). We greatly appreciate suggestions from anonymous referees for the improvement of our paper. Thanks also to the editorial staff.

Declaration of interest

None.

References

- Abiodun, B.J., Salami, A.T., Matthew, O.J., Odedokun, S., 2013. Potential impacts of afforestation on climate change and extreme events in Nigeria. *Clim. Dyn.* 41, 277–293.
- Akinremi, O.O., McGinn, S.M., Barr, A.G., 1996. Evaluation of the Palmer drought index on the Canadian prairies. *J. Climate* 9, 897–905.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements*. FAO Irrigation & Drainage Paper 56. FAO, Rome.
- Allen, K.J., Ogden, J., Buckley, B.M., Cook, E.R., Baker, P.J., 2011. The potential to reconstruct broadscale climate indices associated with southeast Australian droughts from *Athrotaxis* species, Tasmania. *Clim. Dyn.* 37, 1799–1821.
- Alley, W.M., 1984. The Palmer drought severity index: limitations and applications. *J. Appl. Meteorol.* 23, 1100–1109.
- Bacchi, B., Becciu, G., Kottigoda, N.T., 1994. Bivariate exponential model applied to intensities and durations of extreme rainfall. *J. Hydrol.* 155, 225–236.
- Balistracchi, M., Bacchi, B., 2017. Derivation of flood frequency curves through a bivariate rainfall distribution based on copula functions: application to an urban catchment in northern Italy's climate. *Hydrol. Res.* 48, 749–762.
- Barbeta, A., Ogaya, R., Peñuelas, J., 2013. Dampening effects of longterm experimental drought on growth and mortality rates of a Holm oak forest. *Global Change Biol.* 19, 3133–3144.
- Begueria, S., Vicente-Serrano, S., Reig, F., Latorre, B., 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *Int. J. Climatol.* 34, 3001–3023.
- Bezák, N., Šraj, M., Matjaž, M., 2016. Copula-based IDF curves and empirical rainfall thresholds for flash floods and rainfall-induced landslides. *J. Hydrol.* 541, 272–284.
- Bonaccorso, B., Cancelliere, A., Rossi, G., 2015. Probabilistic forecasting of drought class transitions in Sicily (Italy) using Standardized Precipitation Index and North Atlantic Oscillation Index. *J. Hydrol.* 526, 136–150.
- Boroneant, C., Ionita, M., Brunet, M., Rimbu, N., 2011. CLIVAR-SPAIN contributions: seasonal drought variability over the Iberian Peninsula and its relationship to global sea surface temperature and large scale atmospheric circulation. 24–28 October 2011. WCRP OSC: Climate Research in Service to Society, Denver, USA.
- Burton, I., Kates, R.W., White, G.F., 1978. In: *The Environment as Hazard*. Oxford University Press, pp. 240.
- Cavin, L., Mountford, E.P., Peterken, G.F., Jump, A.S., 2013. Extreme drought alters competitive dominance within and between tree species in a mixed forest stand. *Funct. Ecol.* 27, 1424–1435.
- Chang, J.X., Li, Y.Y., Wang, Y.M., Yuan, M., 2016. Copula-based drought risk assessment combined with an integrated index in the Wei River Basin, China. *J. Hydrol.* 540, 824–834.
- Chen, W.Q., 1996. The basic thought about maximum likelihood method and application. *J. Shaoguan Univ. (Nat. Sci. Ed.)* 17, 24–27 in Chinese.
- Chen, L., Singh, V., Guo, S.L., Zhou, J.Z., Zhang, J.H., 2015. Copula-based method for multisite monthly and daily streamflow simulation. *J. Hydrol.* 528, 369–384.
- Correia, F.N., 1987. Multivariate partial duration series in flood risk analysis. In: Singh, V.P. (Ed.), *Hydrologic Frequency Modeling*. Reidel, Dordrecht, pp. 541–554.
- Cunnane, C., 1978. Unbiased plotting positions—a review. *J. Hydrol.* 37, 205–222.
- Drew, D.M., Allen, K., Downes, G.M., Evans, R., Battaglia, M., Baker, P., 2013. Wood properties in a long-lived conifer reveal strong climate signals where ring-width series do not. *Tree Physiol.* 33, 37–47.
- General Administration of Quality Supervision, Inspection and Quarantine of P. R. C., and Standardization Administration of the P. R. C., 2017. *Grades of meteorological drought (GB/T 20481-2017)* (in Chinese).
- Goel, N.K., Seth, S.M., Chandra, S., 1988. Multivariate modeling of flood flows. *ASCE, J. Hydraul. Eng.* 124, 146–155.
- Gringorten, I.I., 1963. Aplotting rule for extreme probability paper. *J. Geophys. Res.* 68, 813–814.
- Guo, S.L., Yan, B.W., Xiao, Y., Fang, B., Zhang, N., 2008. Multivariate hydrological analysis and estimation. *J. China Hydrol.* 28, 1–7 in Chinese.
- Guttman, N.B., 1998. Comparing the Palmer drought index and the standardized precipitation index. *J. Amer. Water Resour. Assoc.* 34, 113–121.
- Hayes, M., 2000. *Drought Indices*. National Drought Mitigation Center, University of Nebraska - Lincoln.
- Heim Jr., R.R., 2002. A review of twentieth-century drought indices used in the United States. *Bull. Amer. Meteor. Soc.* 83, 1149–1165.
- Hulme, M., 1996. Recent climatic change in the world's drylands. *Geophys. Res. Lett.* 23, 61–64.
- IPCC, 2007. In: *Climate Change 2007: The Physical Science Basic: Contribution of Working Group I to the Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp. 235–336.
- Karl, T.R., 1983. Some spatial characteristics of drought duration in the United States. *J. Clim. Appl. Meteorol.* 22, 1356–1366.
- Karl, T.R., 1986. The sensitivity of the Palmer drought severity index and Palmer's Z-index to their calibration coefficients including potential evapotranspiration. *J. Clim. Appl. Meteorol.* 25, 77–86.
- Keyantash, J., Dracup, J.A., 2002. The quantification of drought: an evaluation of drought indices. *Bull. Amer. Meteorol. Soc.* 83, 1167–1180.
- Lau, U., Bosworth, K., 1994. Multivariate kernel estimation of functions of space and time. In: Hipel, K.V., McLeod, A.I.
- Lawrimore, J., Heim Jr., R.R., Svoboda, M., Swail, V., Englehart, J., P. J., 2002. Beginning a new Era of drought monitoring across North America. *Bull. Amer. Meteorol. Soc.* 83, 1191–1192.
- Lei, X.H., Tan, Q.F., Wang, X., Wang, H., Wen, X., Wang, C., Zhang, J.W., 2017. Stochastic optimal operation of reservoirs based on copula functions. *J. Hydrol.* 557, 265–275.
- Li, W., Hou, M., Chen, H., Chen, X., 2012. Study on drought trend in south China based on standardized precipitation evapotranspiration index. *J. Nat. Disasters* 21, 84–90.
- Lorenzo-Lacruz, J., Vicente-Serrano, S.M., López-Moreno, J.I., Begueria, S., García-Ruiz, J.M., Cuadrat, J.M., 2010. The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain). *J. Hydrol.* 386, 13–26.
- McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In: *Preprints, Eighth Conf. on Applied Climatology*. Amer. Meteor. Soc., Anaheim, CA, pp. 179–184.
- Nelsen, R.B., 2006. *An Introduction to Copulas*. Springer, New York.
- Palmer, W.C., 1965. *Meteorological Droughts*. Weather Bureau Research Paper 45. U.S. Department of Commerce, pp. 58.
- Papaioannou, G., Kohnová, S., Bacigál, T., Szolgay, J., Hlavčová, K., Loukas, A., 2016. Joint modelling of flood peaks and volumes: a copula application for the Danube River. *J. Hydrol. Hydromech.* 64, 382–392.
- Paulo, A.A., Rosa, R.D., Pereira, L.S., 2012. Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal. *Nat. Hazards Earth Syst. Sci.* 12, 1481–1491.
- Potop, V., 2011. Evolution of drought severity and its impact on corn in the Republic of Moldova. *Theor. Appl. Climatol.* 105, 469–483.
- Potop, V., Možný, M., Soukup, J., 2012. Drought at various time scales in the lowland regions and their impact on vegetable crops in the Czech Republic. *Agric. For. Meteorol.* 156, 121–133.
- Redmond, K.T., 2002. The depiction of drought: a commentary. *Bull. Am. Meteorol. Soc.* 83, 1143–1147.
- Sackl, B., Bergmann, H., 1987. A bivariate flood model and its application. In: Singh, V.P. (Ed.), *Hydrologic Frequency Modeling*. Reidel, Dordrecht, pp. 571–582.
- Serinaldi, F., Bonaccorso, B., Cancelliere, A., Grimaldi, S., 2009. Probabilistic characterization of drought properties through copulas. *Phys. Chem. Earth* 34, 596–605.
- Sheffield, J., Wood, E.F., Roderick, M.L., 2012. Little change in global drought over the past 60 years. *Nature* 491, 435–438.
- Shiau, J., 2006. Fitting drought duration and severity with two-dimensional copulas. *Water Resour. Manage.* 20, 795–815.
- Silverman, B.W., 1986. *Density Estimation for Statistics and Data Analysis*. Chapman and Hall, New York.
- Sklar, A., 1959. Fonctions de répartition à n dimensions et leurs marges. *Publ. Inst. Stat. Univ. Paris* 8, 229–231.
- Sohn, S.J., Joong-Bae, A., Chi-Yung, T., 2013. Six month-lead downscaling prediction of winter to spring drought in South Korea based on a multimodel ensemble. *Geophys. Res. Lett.* 40, 579–583.
- Song, S.B., Singh, V.P., 2010. Frequency analysis of droughts using the Plackett copula and parameter estimation by genetic algorithm. *Stochast. Environ. Res. Risk Assess.* 24, 783–805.
- Soo-Jin, S., Joong-Bae, A., Chi-Yung, T., 2013. Six month-lead downscaling prediction of winter to spring drought in South Korea based on a multimodel ensemble. *Geophys. Res. Lett.* 40, 579–583.
- Soulé, P.T., 1992. Spatial patterns of drought frequency and duration in the contiguous USA based on multiple drought event definitions. *Int. J. Climatol.* 12, 11–24.
- Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., Stooksbury, D., Miskus, D., Stephens, Scott, 2002. The drought monitor. *Bull. Am. Meteorol. Soc.* 83, 1181–1190.

- Toromani, E., Pasho, M.S.E., 2011. Growth responses to climate and drought in silver fir (*Abies alba*) along an altitudinal gradient in southern Kosovo. *Can. J. For. Res.* 41, 1795–1807.
- Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010a. A multiscale drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J. Clim.* 23, 1696–1718.
- Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., Angulo, M., El Kenawy, A., 2010b. A new global 0.5° gridded dataset (1901–2006) of a multiscale drought index: comparison with current drought index datasets based on the Palmer Drought Severity Index. *J. Hydrometeorol.* 11, 1033–1043.
- Vicente-Serrano, S.M., Lasanta, T., Gracia, C., 2010c. Aridification determines changes in leaf activity in *Pinus halepensis* forests under semiarid Mediterranean climate conditions. *Agric. For. Meteorol.* 150, 614–628.
- Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2011a. Comment on “Characteristics and trends in various forms of the Palmer Drought Severity Index (PDSI) during 1900–2008” by A. Dai. *J. Geophys. Res.* 116, D19112. <https://doi.org/10.1029/2011JD016410>.
- Vicente-Serrano, S.M., López-Moreno, J.I., Gimeno, L., Nieto, R., Morán-Tejeda, E., Lorenzo-Lacruz, J., Beguería, S., Azorín-Molina, C., 2011b. A multi-scale global evaluation of the impact of ENSO on droughts. *J. Geophys. Res.* 116, D20109. <https://doi.org/10.1029/2011JD016039>.
- Vicente-Serrano, S.M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J.J., López-Moreno, J.I., Azorín-Molina, C., Revuelto, J., Morán-Tejeda, E., Sánchez-Lorenzo, A., 2012a. Performance of drought indices for ecological, agricultural and hydrological applications. *Earth Int.* 16, 1–27.
- Vicente-Serrano, S.M., Zouber, A., Lasanta, T., Pueyo, Y., 2012b. Dryness is accelerating degradation of vulnerable shrublands in semiarid Mediterranean environments. *Ecol. Monogr.* 82, 407–428.
- Vicente-Serrano, S.M., Gouveia, C., Camarero, J.J., Beguería, S., Trigo, R., López-Moreno, J.I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., Sánchez-Lorenzo, A., 2013. The response of vegetation to drought time-scales across global land biomes. *Proc. Natl. Acad. Sci. U.S.A.* 110, 52–57.
- Weber, L., Nkemdirim, L.C., 1998. The Palmer drought severity index revisited. *Geogr. Ann.* 80A, 153–172.
- Wells, N., Goddard, S., Hayes, M.J., 2004. A self-calibrating Palmer drought severity index. *J. Clim.* 17, 2335–2351.
- Wilhite, D.A., Glantz, M.H., 1985. Understanding the drought phenomenon: the role of definitions. *Water Int.* 10, 111–120.
- Wilhite, D.A., 2000. Drought as a natural hazard: Concepts and definitions. *Drought A Global Assessment* 1, pp. 3–18.
- WMO, 1975. In: *Drought and Agriculture*. WMO Technical Note No 138, WMO-No 392127, Geneva Switzerland, pp. 113.
- World Meteorological Organization (WMO) and Global Water Partnership (GWP), 2016. *Handbook of Drought Indicators and Indices* (M. Svoboda and B.A. Fuchs). Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2. Geneva.
- Wolf, J.F., Abatzoglou, J., 2011. The suitability of drought metrics historically and under climate change scenarios. In: 47th Annual Water Resources Conference, Albuquerque, NM, 7–10 November 2011. Available from: <http://awra.org/annual2011/doc/pres/S11-Wolf.pdf>.
- Xu, K., Yang, D.W., Xu, X.Y., Lei, H.M., 2015. Copula based drought frequency analysis considering the spatio-temporal variability in Southwest China. *J. Hydrol.* 527, 630–640.
- Yu, M., Li, G., Hayes, M.J., Svoboda, M., Heim, R.R., 2013. Are droughts becoming more frequent or severe in China based on the standardized precipitation evapotranspiration index: 1951–2010? *Int. J. Climatol.* 34, 545–558.
- Yue, S., 2000a. Joint probability distribution of annual maximum storm peaks and amounts as represented by daily rainfalls. *Hydrol. Sci. J.* 45, 315–326.
- Yue, S., 2000b. The bivariate lognormal distribution to model a multivariate flood episode. *Hydrol. Processes* 14, 2575–2588.
- Yue, S., 2001. The Gumbel logistic model for representing a multivariate storm event. *Adv. Water Resour.* 24, 179–185.
- Zhang, D., Chen, P., Zhang, Q., Li, X.H., 2017. Copula-based probability of concurrent hydrological drought in the Poyang lake-catchment-river system (China) from 1960–2013. *J. Hydrol.* 553, 773–784.